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MANNED REMOTE WORK STATION DEVELOPMENT ARTICLE

FINAL REPORT — VOLUME I
BOOK 2
APPENDIX B
TRADE AND DESIGN DEFINITION STUDIES

Prepared for
Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas 77058

By

Grumman Aerospace Corporation
Bethpage, New York 11714

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Introduction

System trades, evaluations and selection have been organized under the appropriate MRWS roles and subsystems. Those trades/evaluations that have an impact on simulator fidelity have been given emphasis in terms of identifying alternate concepts, making a selection, and defining the system approach. Those trades that do not impact simulator fidelity have the issues delineated and future study requirements identified. Some investigations did not result in a trade, per se, but involved selecting a design approach and providing appropriate data.

Summary of Trades/Design Approach

The analysis data contained in this document has been summarized in the following table. Each trade/design approach is titled and numbered the same as the main body of this report so that additional information can be readily obtained. The issues to be resolved, assessment/trade, and future effort are included.

TRADE AND DESIGN DEFINITION STUDIES SUMMARY
(Sheet 1 of 5)

SECTION	TRADE/DESIGN	ISSUE	ASSESSMENT/SELECTION	FURTHER EFFORT
1.	OPEN PLATFORM CHERRY PICKER			
1.1	INTERFACES			
1.1.1	OCP/Orbiter Tiedown	Method of OCP attachment in Orbiter payload bay	Starboard MMU flight support station hard points	• Definition of release mechanism • Crew task simulation of operational preparation
1.1.2	OCP/RMS Interface	Manual vs Remote mating of SRMS to platform	Remotely controlled mating	• Cost analysis of both approaches
1.1.3	Shuttle RMS Access to OCP Stowed in Orbiter	Platform location compatible with RMS reach & EVA access	Starboard MMU flight support station	• Verify RMS attachment to OCP with payloads attached to docking port
1.1.4	Power & Signal Lines Routing to OCP Via RMS	Adequacy of existing RMS wiring to support OCP operations	RMS adequate. Can supply 250 W power & 12 signal lines	• Verify wiring adequacy after OCP designed with particular attention to stabilizer power reqmts
1.1.5	Communication Interfaces	Existing EMU RF communication vs additional RMS mounted antenna	Existing EMU RF communication system	• Verify orbital operations will not unacceptably degrade EVA communications • Consider hardline
1.1.6	Displays & Controls Required to Operate Shuttle RMS via OCP	Determine C&D required to operate OCP & interfaces with existing RMS controls	Operational philosophy, controls & displays, & interface units established	• Simulate OCP operations to verify controls & display adequacy
1.1.7	Shuttle RMS Structural Compatibility	RMS capability to resist astronaut induced loads	RMS unable to react to specified load. Expensive redesign favors addition of stabilizer. Utilize torque capability.	• Determine induced loads & operating procedures
1.1.8	Obstacle Avoidance Approach	Select cost & operationally effective obstacle avoidance method	Rely on crew visual observation to avoid hazards. Add C & W if test results indicate need.	• Simulate assembly operations & analyze C & W need
1.1.9	Shuttle RMS Software Requirement	Adequacy of Orbiter software to meet OCP requirements	Baseline RMS software adequate for OCP control	• If automatic C & W required then software requirements evaluated
1.2	STRUCTURES			
1.2.1	One Man vs Two Man	Crew Size to perform OCP assembly operations	One astroworker adequate for control of RMS & assembly tasks	• Simulate assembly tasks to verify OCP operations
1.2.2	Design Loads	Establish design criteria	Factors of safety, service life, launch & landing criteria	• Determine space operational loads • Select construction materials
1.2.3	Service Fatigue Life	Establish design values	Structure should have fatigue life of 10 years with scatter factor 4	• None
1.3	MECHANICAL			
1.3.1	Stabilizer Single Point vs Multipoint Attachment	Number of stabilizer attachment points to react astroworker induced loads	Single stabilizer minimizes impact on OCP & has better operational flexibility	• Determine stabilizer grapple points
1.3.2	Rate Command vs BFR Stabilizer	Design approach for controlling the stabilizer	Simpler design rate command selected	• Simulate stabilizer tasks to determine control adequacy
1.3.3	Stabilizer Design Conditions	Establish degrees-of-freedom (DOF), accelerations, torque, tip speed and length	Required motion provided by manipulator wrist and stabilizer 6 DOF, other values also determined	• Simulation tests to verify parameters selected
1.3.4	Payload Handling	Concept of payload handling device	Concept for servicing MMS established	• Determine spectrum of items to be handled for common equipment
1.4	ENVIRONMENTAL CONTROL & LIFE SUPPORT			
	Extravehicular Mobility Unit	Adequacy of EMU for OCP life support	Backpack self-contained (standard) EMU adequate & minimizes costs	• None. OCP space operation will verify EMU adequacy

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TRADE AND DESIGN DEFINITION STUDIES SUMMARY
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SECTION	TRADE/DESIGN	ISSUE	ASSESSMENT/SELECTION	FURTHER EFFORT
1.5	DISPLAYS & CONTROLS			
1.5.1	RMS Controller	Selection of hand controllers vs switches	Proportional lever switches tentative selection	• Cost of space qualified controllers & switches • Simulate control of OCP with hand controllers & switches
1.5.2	Control/Display Panel Arrangement	Determine minimum C & D requirements	A panel arrangement containing controllers, 4 switches & caution/warning	• Simulation to determine adequacy of displays
1.5.3	Stabilizer Controller	Determine controller approach for stabilizer operation	Use same controller selected for RMS operation	• Verify adequacy of stabilizer control
1.6	ELECTRICAL POWER			
	Orbiter Umbilical vs Self-Contained Power Source	Is a separate power source required on the OCP?	Existing RMS power transfer capability is adequate for OCP	• Re-evaluation when OCP design firm
1.7	COMMUNICATIONS & DATA			
1.7.1	EMU vs OCP Hardwire	Adequacy of EMU for OCP communications	EMU RF link appears adequate for OCP & negates need for establishing new interfaces	• None. OCP space operations will verify EMU adequacy
1.7.2	OCP Computer or Orbiter Computer	Capability of Orbiter computer to support OCP operations	Orbiter computer to be used for OCP control	• Determine availability of Orbiter computer excess capacity
1.8	CREW ACCOMMODATIONS			
1.8.1	Restraint System Issues	Method of attaching astronaut to OCP	Toe & Heel foot restraint secures boot, easily engaged	• Test restraint in simulator. Additional waist restraint may be required
1.8.2	Tool Requirements	Determine storage for tools	A box 20 x 35 x 60 cm to support 20 kg appears adequate	• Verify volume required when tools specified.
1.8.3	Rescue Provisions	Determine need for OCP rescue provisions	Add traverse provisions to RMS	o Contingency analysis
1.8.4	Lighting	Lighting required for dark side orbital passes	Two over the shoulder lights providing 50 ft candles	• Simulation to check illumination
2	CLOSED CABIN CHERRY PICKER			
2.1	INTERFACES			
2.1.1	C.P./Crane Mechanical Interface	Permanent vs temporary attachment to crane	Permanent attachment simplest to implement	• Reassess when future assembly scenarios firmer
2.1.2	Power & Signal Lines to C.P. via Crane Arm	Method of routing elect. wiring to C.P.	Use internal wiring, similar approach to RMS	• None
2.1.3	Displays & Controls Requirements to Operate Crane from C.P.	Determine displays & controls to operate crane from C.P.	Requirements similar to RMS control from C.P.	• Simulation to determine adequacy of D & C
2.1.4	C.P./Crane Stiffness & Strength Requirements	Determine C.P./crane stiffness & strength	Requirements based on tip force 220 N, end point accuracy & max. tip deflection $<$ 14 cm	• Detailed analysis required for optimum design
2.1.5	Crane Obstacle Avoidance Techniques	Established obstacle avoidance technique	Similar to OCP/RMS obstacle avoidance approach considering ability to bend elbow both ways & upper arm roll joint	• Additional obstacle avoidance algorithm analysis
2.1.6	Visual Aids Required for Obstacle Avoidance	Determine visual side for obstacle avoidance	Aids selected consisting of warning annunciator & CCTV	• Verify provisions during simulation tests

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TRADE AND DESIGN DEFINITION STUDIES SUMMARY
(Sheet 3 of 5)

SECTION	TRADE/DESIGN	ISSUE	ASSESSMENT/SELECTION	FURTHER EFFORT
2.2	STRUCTURE			
2.2.1	Closed Cherry Picker Size & Geometry	Provide design data to layout cabin structure	One man cabin, 1.8 m dia × 2.9 m high	• Operations simulation to verify design
2.2.2	Docking vs Berthing – Size, Location, Quantity	Determine most practical approach to mating MRWS	Berthing to be accomplished by RMS/crane	• None
2.2.3	Hatch Size	Select hatch size compatible with IVA & EVA reqmts	One meter hatch selected for commonality & growth	• Evaluate possibility of reducing hatch size to 0.8m
2.2.4	Vision Requirements – Direct & Indirect	Maximum visibility with minimum window area to limit thermal input	Direct primary view from design eye position at depression angle between -30° to -65° & ±25° azimuth. Expanded secondary viewing areas also established. Add CCTV as needed.	• Determine adequacy of viewing windows during simulation & need for CCTV
2.2.5	Airlock Requirements	Determine need to fulfill airlock role	All MRWS (CP, Crane Turret, Free Flyer, & POTV) function as an airlock for normal & contingency operations	• Verify crane turret air lock in all applications
2.2.6	Subsystem Location – Inside vs Outside vs Mix	Minimize cabin volume requirements by locating equipment external to the pressurized shell	Equipment whose functional requirements permitted mounting external to the cabin were identified	• Review equipment list when design firmer
2.2.7	Design Load Definition	Establish design criteria	Factors of safety, service life, launch & landing criteria established	• Determine space operational loads • Select construction materials
2.2.8	Pressure Vessel Construction	Evaluate design and service life of the structure	The following considerations were addressed: - Construction techniques & load paths - Service fatigue lift - Fracture mechanics analysis	• Fatigue analysis to optimize structure design
2.2.9	Radiation Protection Issues	Determine radiation protection requirements	LEO & GEO requirements assessed for open & closed cabin cherry picker. Open C.P. O.K. for LEO except south atlantic anomoly. Closed C.P. O.K. for LEO & GEO except during solar flares.	• Select cabin design to meet radiation requirements
2.2.10	Meteroid Protection/Issues & Recommendations	Determine radiation protection requirements	Bumper shield thickness 0.019 m, adequate for 10 yr	• None
2.2.11	Radiator – Integrated with Struction vs Separate Installation	Establish radiator mounting location	Radiator mounted on: - Surface of MRWS* - Cantilevered (* selected)	• None
2.2.12	MRWS – Growth Trade	Determine growth capability of MRWS	MRWS assembly was divided into six basis structural elements. Cabin common. Elements may be modified independently providing interfaces maintained	• Detail design should maintain commonality and clean interfaces
2.3	MECHANICAL			
2.3.1	Rotary Bearing Size	Select rotary bearing	Two sizes evaluated & smaller size (0.89 m) selected because of less mass	• Re-evaluate as selection not consistent with 1 m hatch
2.3.2	Master Control Configuration	Determine master control volume available in 6 ft cabin	Controller volume established considering windows, consoles & hatch	• Maintain adequate controller volume during detail cabin design
2.3.3	One vs Two Dexterous Manipulators	Assess need for second manipulator	Two manipulators recommended due to higher productivity & flexibility	• Verify conclusions during simulation tests
2.3.4	Dexterous Manipulator Geometry & Size	Establish manipulator morphology & size	Six DOF plus cabin rotation. Reach of approx. 2 m established based on limit of binocular vision	• Evaluate selection by simulating space operations
2.3.5	Dexterous Manipulator Control Modes	Evaluate control modes	Productivity of BFR and non BFR compared. BFR 6.7 times more efficient	• Verify efficiency of BFR during simulation
2.3.6	Indexing of Manipulators	Establish types of indexing and advantages	Advantages of zone, dual ratio & rate position discussed	• Establish list type for MRWS during simulation tests
2.3.7	Stabilizer – Single-Point vs Three-Point Pickup	Determine advantages & disadvantages of more than one point stabilizer attachment	Single stabilizer - lower cost & mass, higher productivity	• Verify adequacy of single stabilizer during simulation
2.3.8	Stabilizer Design Conditions	Establish basic design parameters	Desired morphology torque & acceleration capability, tip speed and size determined	• Verify design parameters during simulation
2.3.9	Berthing Design Requirements	Establish requirements for berthing design	Stabilizer with appropriate end effector grapples structure & controls closing velocity 1 to 25 cm/sec. MRWS engages Orbiter airlock 3 latch configuration	• Determine expected closing velocities during analysis/simulation

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TRADE AND DESIGN DEFINITION STUDIES SUMMARY
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SECTION	TRADE/DESIGN	ISSUE	ASSESSMENT/SELECTION	FURTHER EFFORT
2.4	ENVIRONMENTAL CONTROL & LIFE SUPPORT			
2.4.1	Shirtsleeve vs Pressure Suit	Select means of maintaining crew pressure environment	Closed cabin provides good mobility & crew comfort	• None
2.4.2	Cabin Pumpdown vs Blowdown	Determine MRWS design for evaluating the cabin gas	It is an advantage to reclaim cabin gas, however, for infrequent pressure reductions & emergency situations, blowdown recommended.	• None
2.4.3	$LiOH_2$ vs Amine Air Purification	Select MRWS approach to air purification	For long term high usage MRWS amine system selected also humidity control inherent in solid amine system	• None
2.4.4	Sublimator vs Radiator	Determine most practical heat rejection approach	Quantity of water for sublimator high & as radiator area is available, radiator selected	• None
2.4.5	ECLS Design Conditions	Determine basic design conditions	Design parameters selected: volume, environment, metabolic, consumables & interior heat load	• Review design volumes as a consequence of analysis & simulation tests
2.5	CONTROLS & DISPLAYS			
2.5.1	Display Technology Options	Review display options applicable to MRWS	Three types of displays reviewed: electron beam, matrix addressed & option	• Final display approach after simulation tests
2.5.2	Console – Function Layout Area	Establish required displays and design tentative layout	Displays were selected & located on panel layout	• Verify selected displays & operation in simulation tests
2.5.3	Dexterous Manipulator Controller	Select type of controller for operation of dexterous manipulator	BFR selected as productivity highest with this approach	• Establish productivity during simulation
2.6	ELECTRICAL POWER SYSTEM			
2.6.1	Power Source – Remote vs Load	Recommend location of power source	To minimize mass & volume of MRWS, it is recommended that power source be located at base of C.P. arm. Battery in MRWS for emergency power	• None
2.6.2	Electrical Loads	Establish power requirements of equipment to size power source	Equipment power load tabulated	• Update power requirements when actual hardware selected
2.7	CREW ACCOMMODATIONS			
2.7.1	Rescue Provisions (Cabin MRWS)	Determine design considerations for crew rescue	Cabin pressure maintenance required for donning of PRS, Backup hatch operation required	• Simulate contingency operations
2.7.2	Tools	Assess tools required for storage	Tools listed	• Update tool list after simulated operations
3	CRANE TURRET DELTA REQUIREMENTS FROM CLOSED CABIN			
3.1	INTERFACES			
	MRWS Crane Turret Arrangement	Establish general arrangement of crane turret	An integral MRWS cabin and base selected	• Refine requirements based simulations
3.2	MECHANICAL			
3.2.1	Crane Control – Resolved Rate vs BFR	Determine mode of control system	Comparison of both methods of control & determined resolve rate best	• Evaluate resolve rate system & select force feedback method
3.2.2	Controller Configuration	Select resolved rate mode of control	Three configurations evaluated: - 2 three DOF - 1 six DOF - 1 three DOF with switch selection for trans. or rotation	• Simulate operations to determine best mode of control
3.3	ENVIRONMENTAL CONTROL & LIFE SUPPORT			
	Cabin Pump-Down vs Blow Down	Review blow-down used for CP MRWS for crane turret	If the crane turret is used as an air lock with repeated depressurations then pumpdown is advantageous	• Review usage of crane turret and if desirable add pumpdown kit to MRWS cabin

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TRADE AND DESIGN DEFINITION STUDIES SUMMARY
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SECTION	TRADE/DESIGN	ISSUE	ASSESSMENT/SELECTION	FURTHER EFFORT
3.4	DISPLAYS & CONTROLS			
	CCTV Requirements	Determine location of CCTV cameras and features required	TV cameras should be mounted on the crane elbow and wrist. Additional cameras may be mounted on turret MRWS & C.P. MRWS. Camera parameters, lighting, controls & reticle discussed	• Simulation tests will verify camera location selected
3.5	ELECTRICAL POWER			
	Crane Power Requirements	Determine crane power	Max. torque and speed used to estimate power needed (2.3 kW)	• Operational tests to verify design assumptions
4	FREE FLYER DELTA REQUIREMENTS FOR CLOSED CABIN			
4.1	STRUCTURE			
4.1.1	Additional Equipment	Identify additional equipment so that mounting structure available in detail design	Equipment listed, location & mass data included	• Verify equipment during simulation & detail design
4.1.2	Jet Mounting Locations	Provide jet mounting for rotational & translation	Four thruster clusters and three thruster evaluated. Selected 18 thrusters in 6 clusters of three	• Verify thruster arrangement during future simulation/analysis
4.2	CONTROLS & DISPLAYS			
4.2.1	FLIGHT & PROPULSION	Determine additional controls & displays needed to fly the MRWS	Functions unique to the C.P. MRWS were deleted from the C.P. MRWS and flt control/propulsion C & D were added	• Verify adequacy of C & D during simulation
4.3	ELECTRICAL POWER			
4.3.1	ADDITIONAL POWER	Determine additional power required by free flyer	Equipment listed & power estimates provided	• Verify power when detailed design studies completed
4.3.2	Battery vs Fuel Cells	Evaluate alternate power sources & determine most practical	Stored energy systems only practical source for non-fixed base MRWS. Fuel cells provide greatest flexibility & long continuous service	• Review selection during detailed design studies
4.4	PROPULSION			
4.4.1	Control Authority Requirements	Establish rotational control authority for free flyer	Lunar Module flight experience was reviewed and 10 deg/sec^2 rotational acceleration was established	• Conduct analysis to determine if acceleration valid
4.4.2	Task Sizing	Determine propellant requirements so that tanks can be sized	Propellant estimate for translation, station keeping, attitude & rotation were determined requiring 225 lb of N_2H_4. Tank size 2 ft dia or 4 16.5 in dia	• Simulated operations to verify in-flight maneuvers

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Section 1

OPEN CHERRY PICKER

1.1 INTERFACES

1.1.1 OCP/Orbiter Tiedown

The Manned Remote Work Station (MRWS) Open Cherry Picker (OCP) when mounted to the end of the Shuttle Remote Manipulator System (RMS) is used to support spacecraft servicing and construction operations of near-term missions. For these missions, the Orbiter should provide for the stowage and support of the OCP in the payload bay. The OCP should be stowed in the payload bay area that would minimize the impact to the payload envelope and provide the RMS accessibility to the OCP cabin for mechanical mating of the two. The OCP tiedown should be capable of supporting the stowed OCP for the environments induced during Shuttle Launch/Entry as defined in NASA document JSC07700, Vol. XIV, "Space Shuttle System Payload Accommodations."

1.1.1.1 Design Approach - The forward 48 in. (X_o579-X_o627) of the payload bay is reserved when extra vehicle or activity (EVA) operation are planned on any mission. There are two candidate locations within the reserved envelope that are favored for OCP storage/tiedown. One location (Figure 1) is the Flight Support Station used for Manned Maneuvering Unit (MMU) donning/egress which is located at the forward end of the payload bay near the airlock. Structural hard points exist at this location and the area is accessible to the RMS for RMS/OCP mechanical mating. The RMS engages the OCP (it is unlatched from tiedown position) and the RMS positions the OCP near the forward EVA hatch for crew operations. At this location, the crewman can prepare the OCP for orbital operations.

The second stowage area is on the payload bay forward bulkhead (Figure 1); here the OCP is mounted on the bulkhead to one side of the airlock. This location is also accessible to the RMS and EVA crewman. An issue with this location is the availability of structural hard points to support the OCP for launch/entry loads.

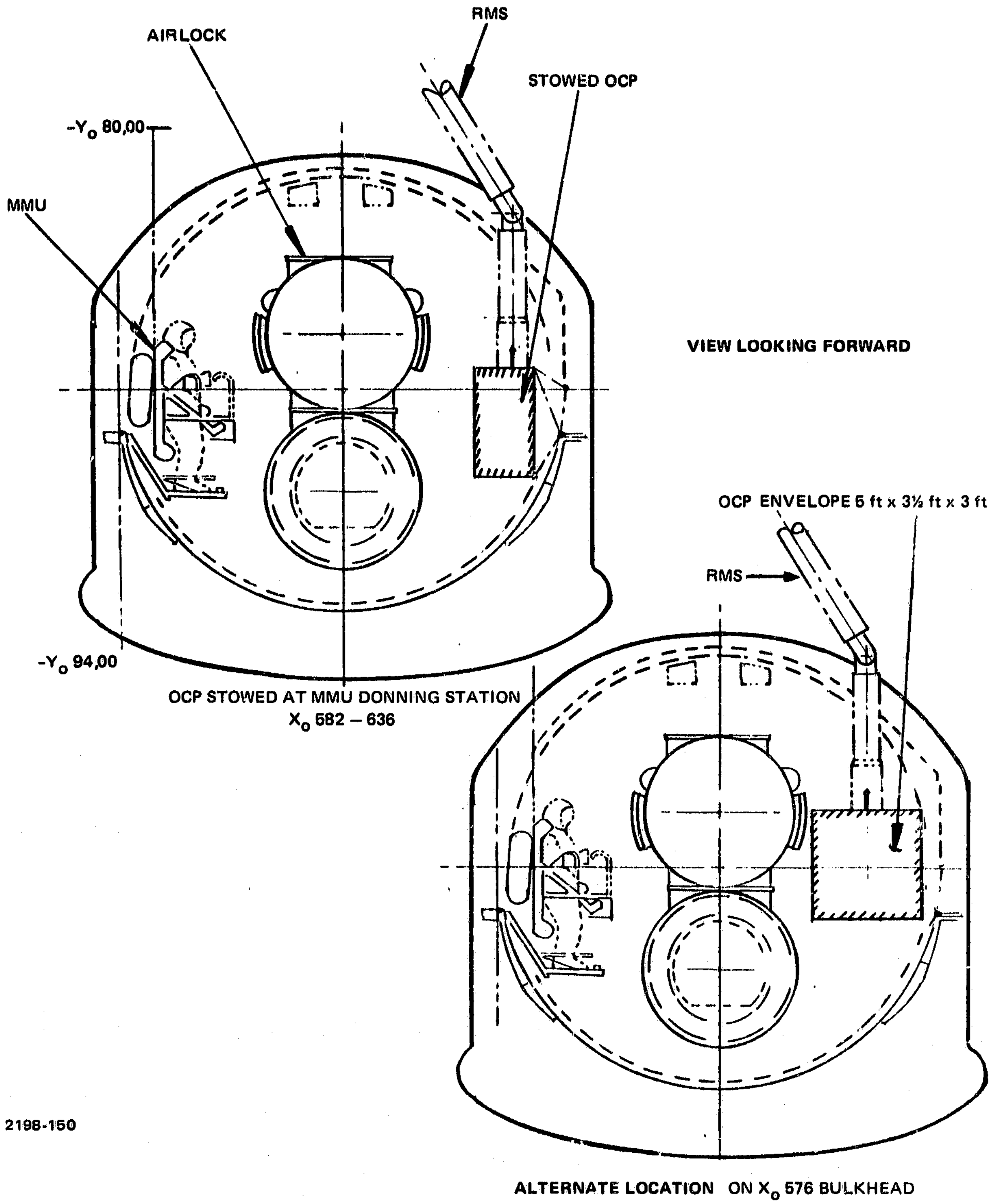

Figure 1. OCP Stow Locations in Cargo Bay

Other areas outside of the reserved EVA envelope were considered but not pursued because of their impact to payload envelope or the extended EVA routing required of the crewman in the payload bay.

1.1.1.2 Selected OCP/Orbiter Tiedown Definition - The MMU donning station location, which contains existing structural hard points (X_o582 and 636, Y_o44), has been selected as the stow area for the OCP during Orbiter launch/entry. This area provides the accessibility needed for RMS/OCP mating and subsequent positioning of the OCP near the forward EVA hatch for crew deployment of the OCP and ingress.

1.1.1.3 Required Simulation Analysis - Simulate the tasks required of the RMS to reach the OCP stow station located in the payload bay and perform the operations necessary to effect the RMS/OCP mechanical mating. Also, simulate the crew tasks required to deploy the OCP, ingress and prepare the OCP for orbital operations.

1.1.2 OCP/RMS Interface

The MRWS interfaces with the Shuttle Remote Manipulator System (RMS) in the Open Cherry Picker (OCP) configuration. The OCP requires a mechanical and electrical attachment at the end of the Remote Manipulator.

1.1.2.1 Design Approach - An approach for this mechanical interface is to clamp the OCP to the end effector of the RMS (Figure 2). The interface mating is done manually by the EVA astronaut. In this approach, the OCP is stowed in the forward portion of the payload bay close to the Shuttle egress hatch. This location reduces the astronaut EVA route and thereby reduces the amount of equipment that lies along the route that would have to be man-rated. The existing payload bay MMU donning station is a good candidate stow area for the OCP. With the EVA astronaut stationed at the OCP stow area, the Remote Manipulator is activated and brought to the stow area. The end effector is roughly aligned with the opened clamps of the OCP. The EVA astronaut then calls for relaxing of the RMS. Once this is done, he positions the RMS end effector within the open clamps and latches and locks the clamps. He then mates the umbilical connectors which provide the electrical power and signal cabling to the OCP. The astronaut then releases the latches of the OCP retention/stow device and mounts the platform for final cherry picker checkout.

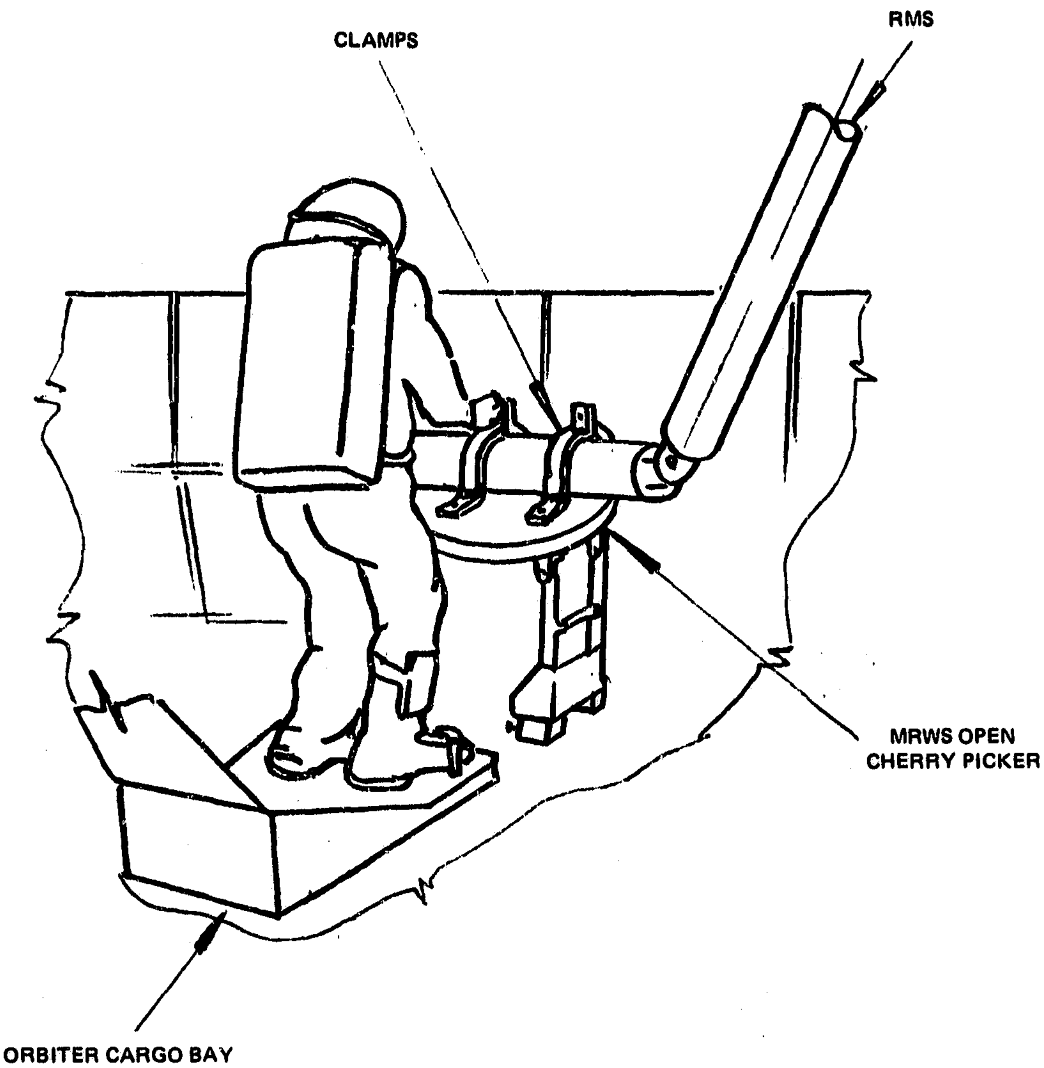

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Figure 2. OCP/Shuttle Mechanical Interface

An alternate approach is automatic mechanical/electrical mating of the RMS and OCP, which is remotely controlled form the Shuttle payload RMS station. For this approach, the RMS is configured with a Snare-Type End Effector and the cherry picker with the grapple fixture (Figure 3).

Using this approach, the cherry picker can be stowed at launch anywhere in the payload bay within reach of the RMS. Controlled from the Orbiter RMS station, the RMS is brought to the cherry picker stow area to snare the grapple fixture of the OCP. When this is accomplished, the end effector is actuated to effect a hard lock-on mechanical/electrical mate. This interface is remotely verified via the umbilical. Upon completion of OCP checkout the RMS operator activates the tiedown latches of the OCP retention/stow device releasing the OCP from the stowed position. The OCP is then brought to the Shuttle egress hatch where the EVA astronaut mounts the OCP, positions himself at the control console, and takes over the control of the RMS in preparation for on-orbit tasks.

1.1.2.2 Selected OCP/RMS Mechanical Interface - It is recommended that the alternate approach be selected for the MRWS Open Cherry Picker configuration. This remotely controlled mechanical/electrical mating approach does not expend EVA time and offers a greater payload bay stow area selection which may better suit user requirements/costs.

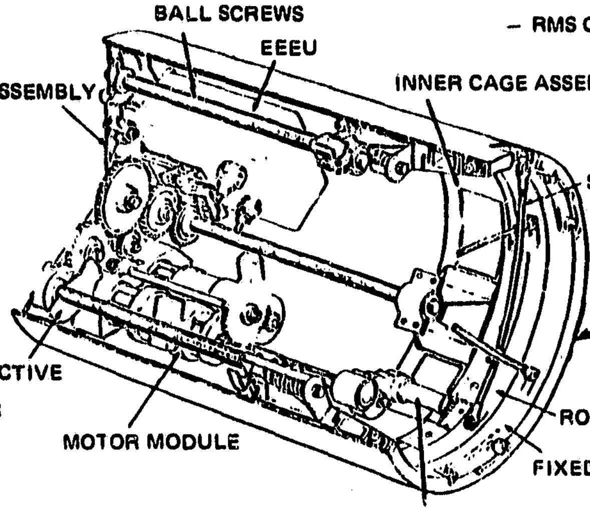
1.1.2.3 Further Efforts and Analysis Required - Cost analysis (trades) of automatic versus manual approach is required.

1.1.3 Shuttle RMS Access to OCP Stowed in Orbiter

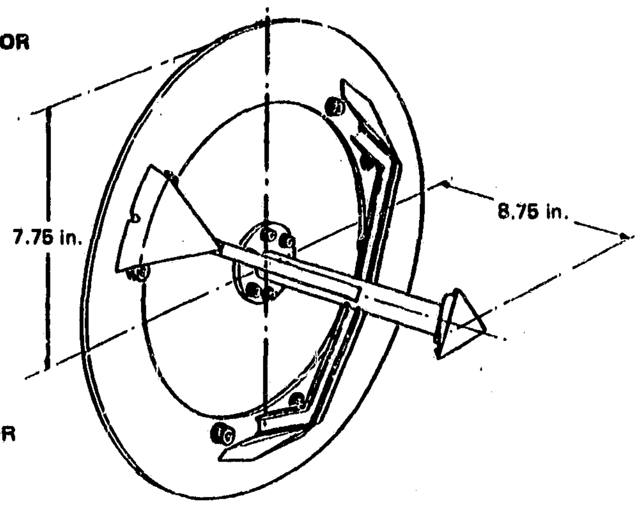
The Shuttle RMS is capable of reaching any point within the cargo bay with the exception of some small areas at the aft end of the bay and around the shoulder attachment point.

However, when assessing the capability of the Shuttle RMS to pick up and manipulate the cherry picker from its stowed position in the cargo bay, a number of factors must be considered:

- Shuttle RMS articulated position required to reach the cherry picker grapple fixture
- Obstacles between the cherry picker and the Shuttle RMS, e.g., other payloads in the cargo bay



SNARE-TYPE RMS END EFFECTOR



OCP MOUNTED GRAPPLE FIXTURE

INTERFACE REQUIREMENT

- MECHANICAL – CANADIAN SNARE-END EFFECTOR & GRAPPLE FIXTURE
  - PRECAPTURE MISALIGN LIMITS – 4 in.
    $\pm 15^{\circ}$
  - CAPTURE SPEED – 0.33 TO 0.95 ft/sec
  - RIGIDIZE SPEED – 8 to 5.7 in./sec
  - TORQUE CAPABILITY – 350 ft-lb
  - RELEASE IMPULSE – 0.3 lbf-sec
- ELECTRICAL
  - MRWS POWER = TBD
- SIGNAL
  - ATTITUDE & TRANSLATION HAND CONTROLLER SIGNALS
  - RMS CONSOLE SIGNALS
  - ECLS SIGNALS

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Figure 3. OCP/Shuttle RMS Mechanical Interface Definition

- Movements of the Shuttle RMS required to remove the cherry picker from its stowed position in the cargo bay
- Vision (direct or CCTV) required to grapple and manipulate the cherry picker.

An initial assessment of these parameters indicates the cherry picker should be stowed in the forward section of the cargo bay.

Final assessment of the cherry picker stowage position should consider the aforementioned factors plus the overall Shuttle payload CG position and any EVA requirements.

With reference to the preliminary layout (Figure 4) the left-hand location (assumed grapple coordinates $X_o = 585$, $Y_o = -72$, $Z_o = 410$) is not possible. The righthand location (assumed coordinates $X_o = 615$, $Y_o +70$, $Z_o = 420$) is possible.

1.1.4 Power and Signal Line Routing to OCP via RMS Arms

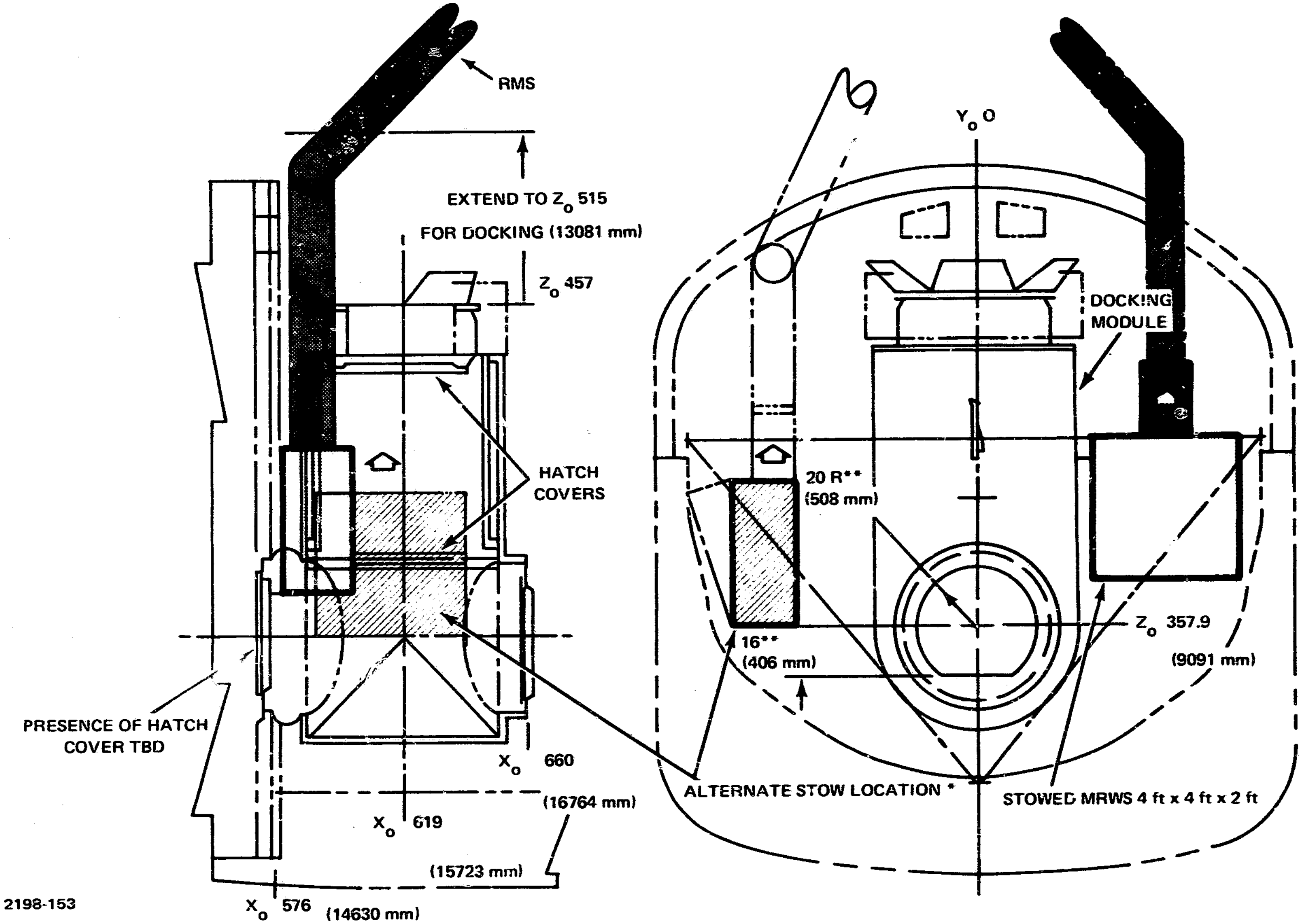
The OCP will be treated as a Special Purpose End Effector (SPEE). The Shuttle RMS has dedicated wiring for any SPEE and it is proposed that this wiring be utilized.

The wiring incorporated at present is shown in Figure 5. This shows the number of cores and wire sizes from the orbiter C&D panel through to the SPEE. It can be seen that the wiring comprises 12 signal lines which are distributed in two twisted shielded pairs, one shielded quadruple and four single conductors. Cable cores are available for heater power to the SPEE which could be used for signal lines if heater power were not required.

The power to the SPEE is switched at the Standard End Effector. Maximum power available for the SPEE is 150 W through the power cables and 100 W for the heater power. The estimate for power for the C&D panel and the hand controllers excluding heater power is 40 W.

1.1.5 Communication Interface

The present Orbiter-to-EVA communication system should be satisfactory. However, the cherry picker may be driven into positions in which the operator is shielded from the Orbiter and he may lose contact. This may be alleviated by having an antenna mounted in the cherry picker which is hardwired to the Orbiter via the



* AN ALTERNATE LOCATION IS THE MMU DONNING STATION LOCATED BETWEEN X_o 582 & X_o 636

** DIMENSIONS IN in. – THESE DIMENSIONS RELATE TO PASSAGEWAY SIZE

Figure 4. Candidate Cherry Picker Stowage Locations in Orbiter Payload Bay

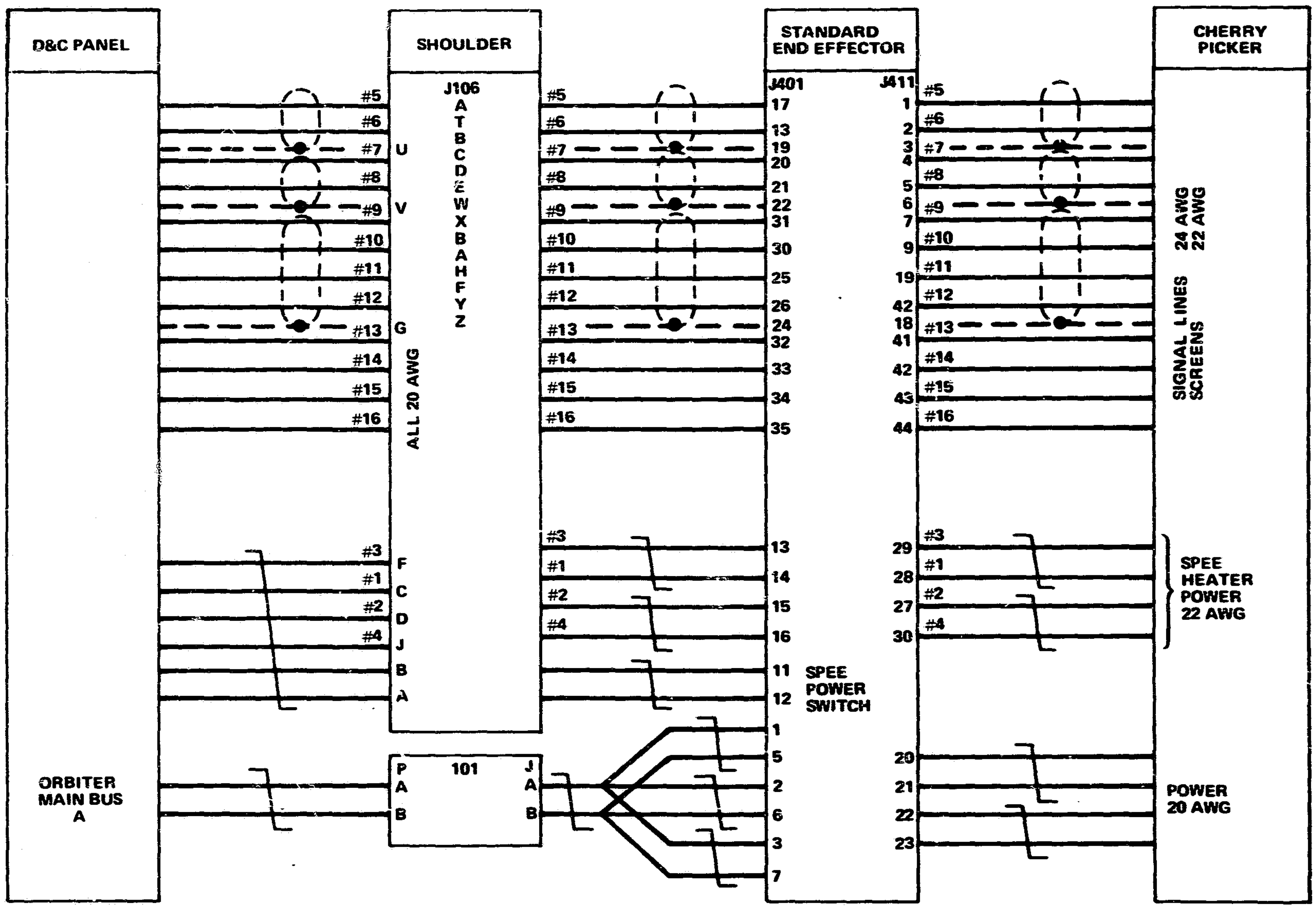


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Figure 5. Orbiter/SEE/SPEE Wiring

SPEE wiring. This would also require some modification to the EVA communication system hardware within the Orbiter.

1.1.6 Controls and Displays Required to Operate Shuttle RMS via OCP

The RMS system block diagram is shown in Figure 6. The C&D subsystem of the RMS provides, in conjunction with the Orbiter CRT Display and Keyboard the essential interface between the RMS Operator and the subsystems of the Remote Manipulator. The Manipulator Control Interface Unit (MCIU) controls the flow of data to and from the C&D panel, the GPC and the Arm Based Electronics (ABE).

The main data flow between the MCIU and the C&D is accomplished using serial buses (MCIU data and C&D response bus). The exceptions to this data are the rate demand signals from the hand controllers. These signals of x, y, z, roll, pitch, and yaw rate demand are hardwired into the MCIU.

There are two major requirements when considering the controls and displays required for the cherry picker:

- Controls and displays required at the cherry picker
- The best method of transmission of these signals.

In order to decide what controls are required at the cherry picker to operate the arm, it is necessary to decide upon the philosophy of the system.

1.1.6.1 Control and Display Philosophy - The following philosophy was developed:

- Arm control station can only be selected from the Orbiter
- When cherry picker control station selected, the system operates in manual augmented mode only
- Cherry picker operator has primary display and control functions only (single-joint control or direct control not provided)
- Cherry picker operator is to have control and display functions in a form in which a minimum of retraining between Orbiter control and cherry picker control will be necessary
- The cherry picker will operate in the payload coordinate system or a modified end effector coordinate system (Figure 7)

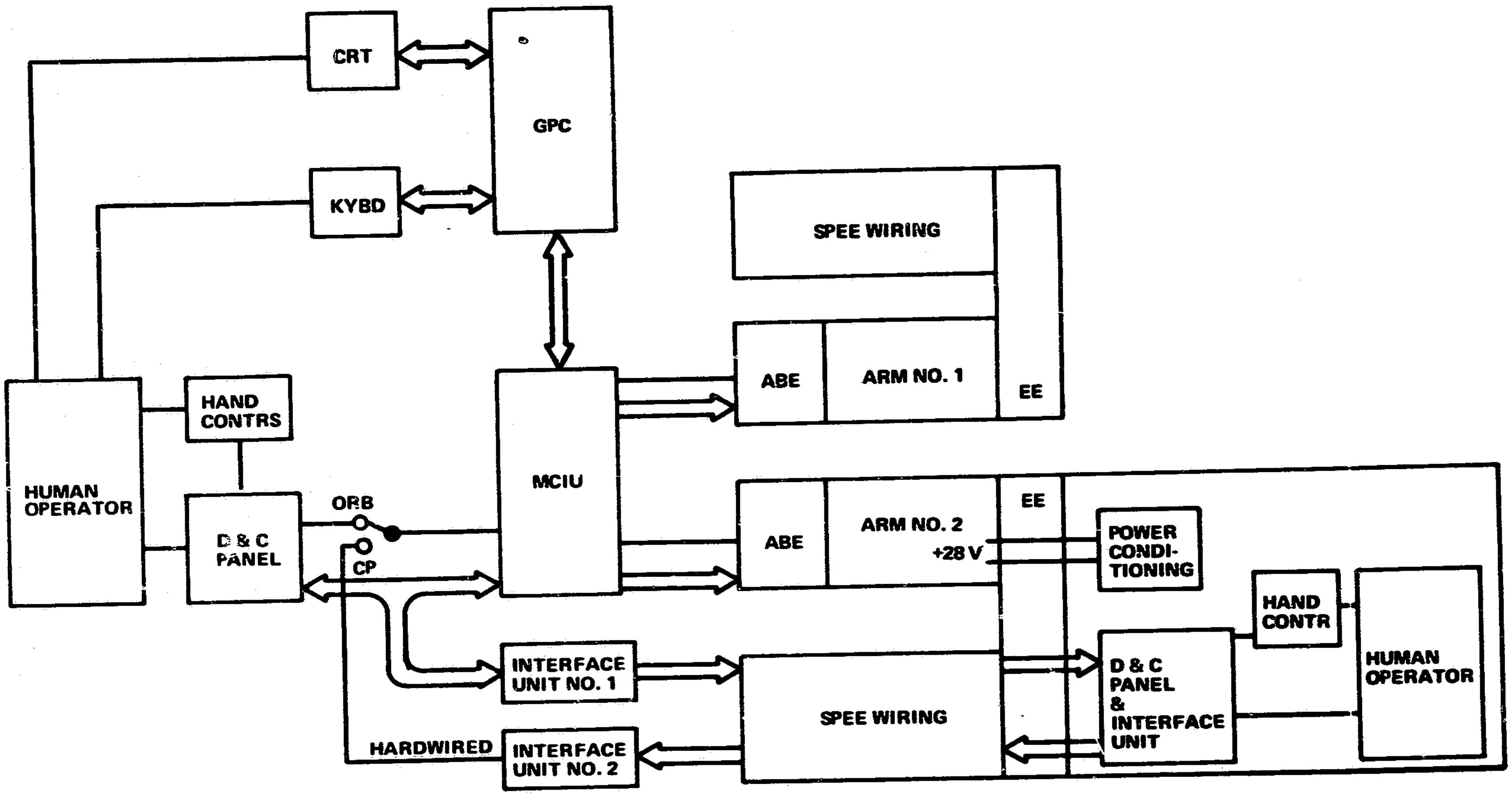

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Figure 6. RMS System Block Diagram

- If operating other arm, then cherry picker arm will be stationary and a TV monitor will be required. Other arm will operate in its end effector co-ordinate system or in a line of sight coordinate system (Figure 8).

With this philosophy in mind, the control inputs will be considered.

1.1.6.2 <u>Control System Requirements and Evaluation</u> - The cherry picker operator is required to provide inputs to the control system; a choice of various alternatives is given in Table 1. It must be noted that the cherry picker operator will be in his EVA suit and that he will not be as dextrous as normal. It is considered that although option (a) is the most complex, it is the method used in the Orbiter and is considered to be the best method from experiments carried out on simulators. The hand controllers will not necessarily be the same as those in the Orbiter but will have the same functions available.

The only other command necessary is to be able to apply the brakes from the cherry picker so they can be used either in an emergency to stop one or both arms from the cherry picker. It would be possible to control the arm from the cherry picker with no monitoring at all; however, the cherry picker operator will fly the cherry picker with his back to the arm (looking at the payload) or at best a side view of the arm and could drive the arm into configurations at which a caution would be annunciated. If this occurs, the cherry picker operator will lose control. It is, therefore, considered necessary that the caution indicators be provided at the cherry picker. The Caution Annunciators are given in Table 2.

The second problem is to obtain the data required for monitor and control and to transmit it over the length of the arm. Various methods of transmitting the data are given in Table 3. Digital data transmission is considered the most suitable, considering the number of signals required and the length of the cable that the transmission is made over. To obtain the data for transmission, it is proposed to interface with the MCIU to C&D panel data bus and to pick off the signals that are being transmitted to the C&D panel in the Orbiter. This panel will still monitor all the signals even when the cherry picker is in operation.

The caution functions are all contained in one single word on the MCIU to C&D bus (Table 4).

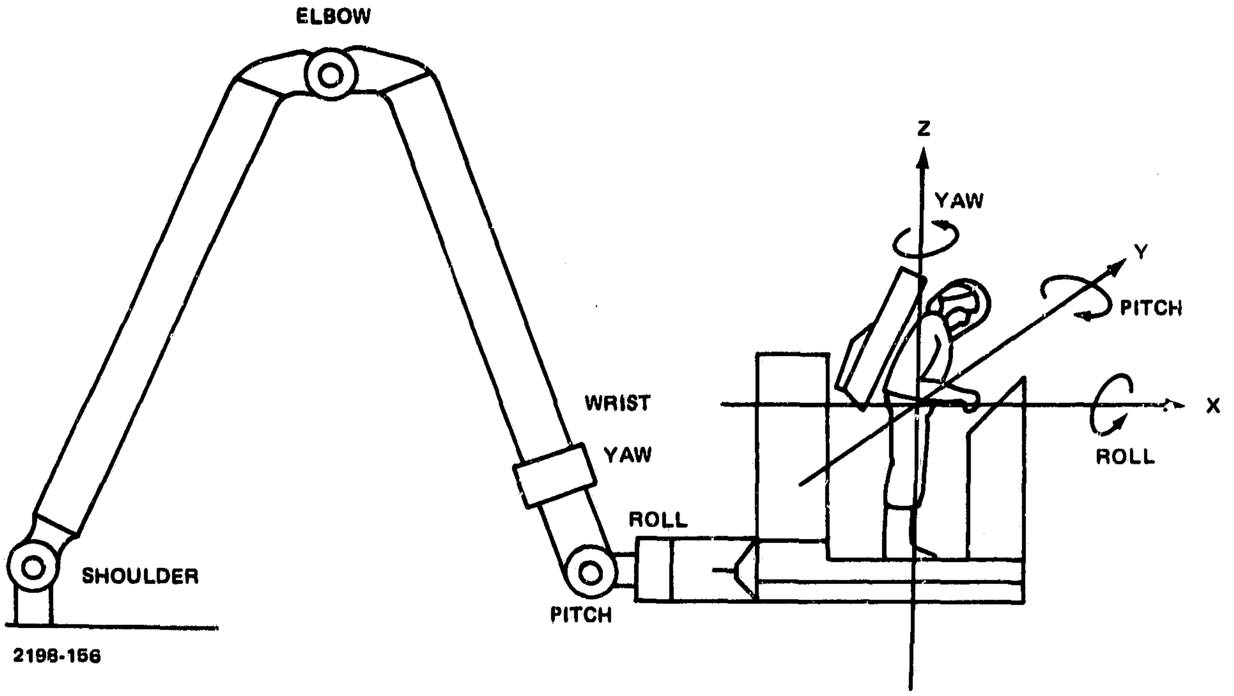

Figure 7. Cherry Picker Coordinate System

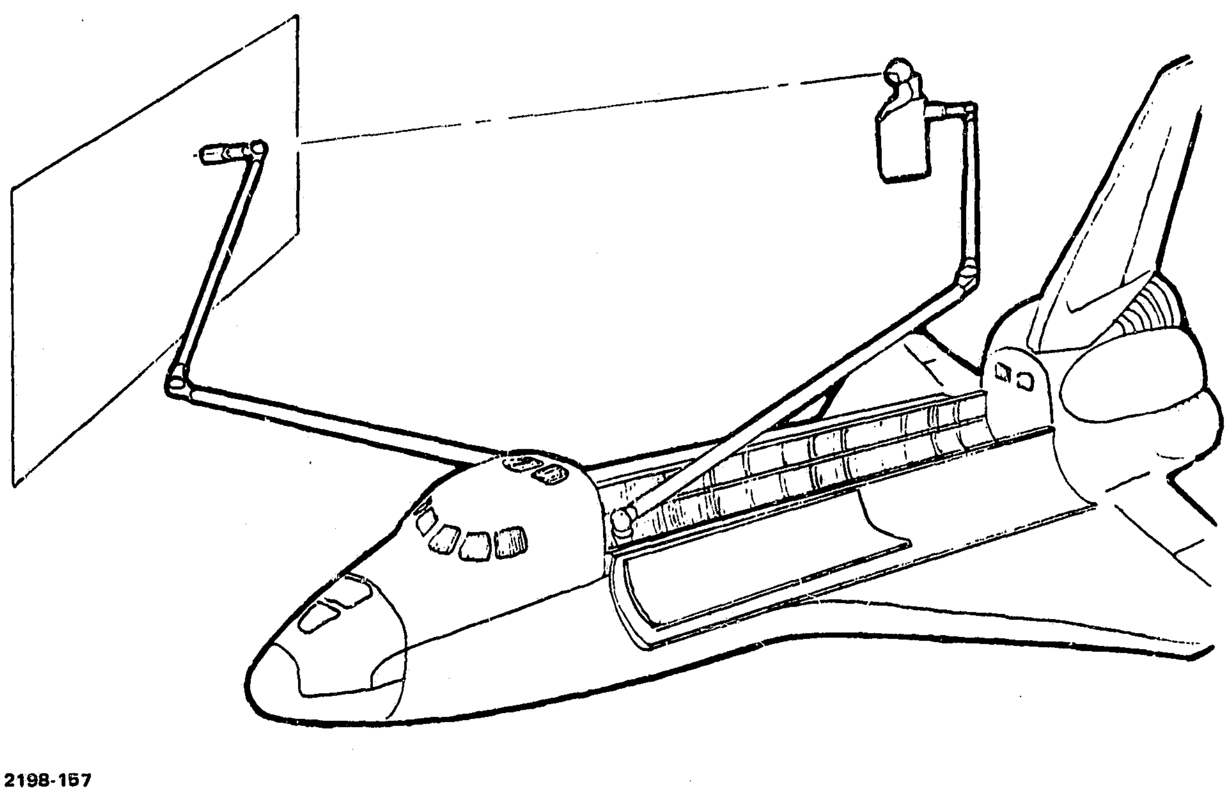

Figure 8. Line-of-Sight Coordinate System for Second Arm

TABLE 1

CHOICE OF CONTROLLER

METHOD OF APPLYING INPUT COMMANDS	ADVANTAGES	DISADVANTAGES
(a) TRANSLATIONAL HAND CONTROLLER ROTATIONAL HAND CONTROLLER SWITCH BETWEEN COARSE & VERNIER	– SIMILAR CONTROL TO THAT USED IN ORBITER (NO OPERATOR RETRAINING) – APPLIES INPUT RATE PROPORTIONAL TO HAND CONTROLLER POSITION – INPUTS CAN BE APPLIED SIMULTANEOUSLY IN ALL AXES GIVING MAXIMUM EFFICIENCY	– COMPLEX CONTROLLERS REQUIRING ELECTRONIC CONDITIONING – INCREASED POWER REQUIREMENT
(b) SINGLE-HAND CONTROLLER SWITCH BETWEEN ROTATIONAL & TRANSLATIONAL SWITCH BETWEEN COARSE & VERNIER	– SINGLE CONTROLLER LEAVES OPERATORS OTHER HAND FREE – OPERATOR COULD TURN ROUND TO WATCH ARM CONFIGURATION AS WELL AS PAYLOAD – APPLIES INPUT RATE PROPORTIONAL TO HAND CONTROLLER POSITION – INPUTS CAN BE APPLIED IN THREE AXES SIMULTANEOUSLY – REDUCES POWER REQUIREMENTS	– REQUIRES OPERATOR RETRAINING, OPINION IS THAT TO SWITCH BETWEEN MODES COULD BE VERY CONFUSING – COMPLEX CONTROLLER REQUIRING ELECTRONIC CONDITIONING
(c) INDIVIDUAL SWITCHES FOR x y z ROLL PITCH YAW EACH SWITCH HAVING POSITIVE/OFF/ NEGATIVE CONSTANT RATE	– SIMPLE – ECONOMICAL – RELIABLE	– APPLIES STEP INPUT INTO ARM WHICH CAN CAUSE OSCILLATIONS – DIFFICULT FOR OPERATOR TO OPERATE IN MORE THAN ONE AXIS SIMULTANEOUSLY – REQUIRES OPERATOR RETRAINING FROM ORBITER CONTROLS
(d) ROTARY SWITCH FOR x y z ROLL PITCH YAW SINGLE SWITCH FOR POSITIVE/OFF/ NEGATIVE CONSTANT RATE	– SIMPLE – ECONOMICAL – RELIABLE	– APPLIES STEP INPUT WHICH CAN CAUSE OSCILLATIONS – CAN ONLY BE OPERATED IN ONE AXIS AT A TIME WHICH IS INEFFICIENT – REQUIRES OPERATOR RETRAINING FROM ORBITER CONTROLS

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TABLE 2

CAUTION ANNUNCIATORS

CAUTION	SINGULAR	–	INDICATES THAT THE CONFIGURATION OF THE MANIPULATOR ARM IS APPROACHING AN ARM SINGULARITY CONDITION
CAUTION	CONTR ERR	–	INDICATES CERTAIN JOINT ABNORMAL CONDITIONS WHICH MAY NOT BE DETECTED BY BITE
CAUTION	STBD TEMP	–	INDICATES THAT THE TEMPERATURE OF A UNIT WITHIN THE STARBOARD MANIPULATOR ARM HAS EXCEEDED THE PREDETERMINED CAUTION THRESHOLD
CAUTION	CHECK CRT	–	INDICATES THAT A FAILURE MESSAGE IS AVAILABLE TO THE OPERATOR ON THE ORBITER CRT
CAUTION	REACH LIM	–	INDICATES THAT THE MANIPULATOR ARM HAS REACHED A CONFIGURATION THAT ONE OF THE JOINTS IS CLOSE TO ITS REACH LIMIT
CAUTION	PORT TEMP	–	INDICATES THAT THE TEMPERATURE OF A UNIT WITHIN THE PORT MANIPULATOR ARM HAS EXCEEDED THE PREDETERMINED CAUTION THRESHOLD

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TABLE 3

DATA TRANSMISSION

METHOD OF TRANSMISSION	ADVANTAGES	DISADVANTAGES
(a) INDIVIDUAL HARDWIRED	– SIMPLE – RELIABLE	– INEFFICIENT – LIMITS NO. OF SIGNALS WHICH CAN BE TRANSMITTED TO NO. OF WIRES AVAILABLE – TRANSMISSION OF ANALOG SIGNAL THROUGH 80 FT MAY CAUSE ATTENUATION/NOISE PROBLEM – NO SCOPE FOR EXPANSION
(b) ANALOG MULTIPLEX	– SIMPLE – RELIABLE – WELL PROVEN TECHNIQUES – EFFICIENT – MANY SIGNALS DOWN FEW WIRES – SCOPE FOR EXPANSION	– TRANSMISSION OF SWITCHING ANALOG SIGNALS THROUGH 80 FT MAY CAUSE ATTENUATION/NOISE PROBLEM
(c) DIGITAL DATA TRANSMISSION	– RELIABLE – WELL PROVEN TECHNIQUES – EFFICIENT – NO ATTENUATION PROBLEM – SCOPE FOR EXPANSION	– REQUIRES DATA CHECKING PROCEDURES – MORE COMPLEX – REQUIRES INCREASED ELECTRONICS

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TABLE 4

MCIU TO C&D DATA

WORD	ADDRESS BIT 0,1,2,3,4	PARAMETER	BIT LOCATION
1	00001	ABE FAILURE WARNING	5
		STBD TEMP CAUTION	6
		PORT TEMP CAUTION	7
		SOFTWARE STOP SELECT	8
		SINGULARITY CAUTION	9
		REACH LIMIT CAUTION	10
		EE DERIGIDIZED WARNING	11
		EE RELEASED WARNING	12
		CHECK CRT CAUTION	13
		CONTROL ERROR CAUTION	14

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The hand controllers will provide rate demand signals proportional to the deflection of the hand controller. These signals may be either analog or digital but will be converted to digital signals for transmission. A block diagram of the proposed OCP system is given in Figure 9.

If single-drive mode i.e., only one joint is driven at any given time, is required to provide obstacle avoidance during operations, then it will be necessary to include a joint selection switch and a joint increase and decrease switch into the Controls and Displays panel in the cherry picker (Figure 10).

The information from the cherry picker will be transmitted via the data bus to the Orbiter C&D panel where it will be switched via the cherry picker/Orbiter control station switch, and the signals will be substituted for those from the Orbiter C&D panel switches. The information required is:

Joint Select	SH YAW
Joint Select	SH PITCH
Joint Select	ELB PITCH
Joint Select	WR PITCH
Joint Select	WR YAW
Joint Select	WR ROLL

Direct Drive Clockwise (+ve)
Direct Drive Counter Clockwise (-ve)
Single Mode Select
Control Mode Enter

Provision should be made to inhibit inputs from the C&D panel when the cherry picker control station is selected. Selection of manual augmented or single-mode drive when the cherry picker control station is selected could be made in either the Orbiter or the cherry picker. The easier method for the hardware would be to select the mode in the Orbiter because this selection switch is already there. However, this may not be preferred from the operational viewpoint.

1.1.7 <u>Shuttle RMS Structural Compatibility</u>

Table 5 summarizes the force and torque capabilities of the RMS referred to the end effector. Exertion of forces in excess of these will cause the RMS to backdrive.

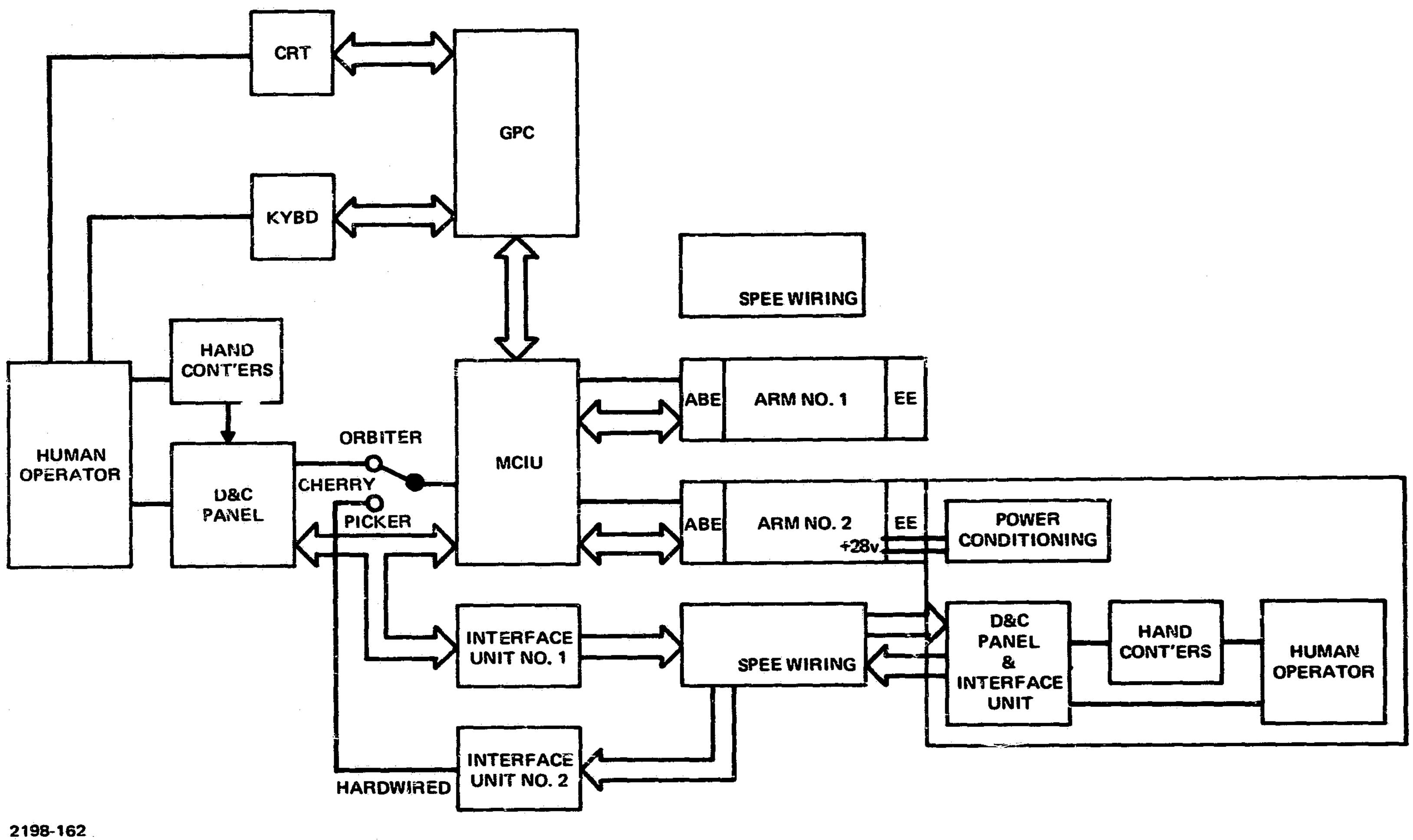

Figure 5. Open Cherry Picker System Block Diagram

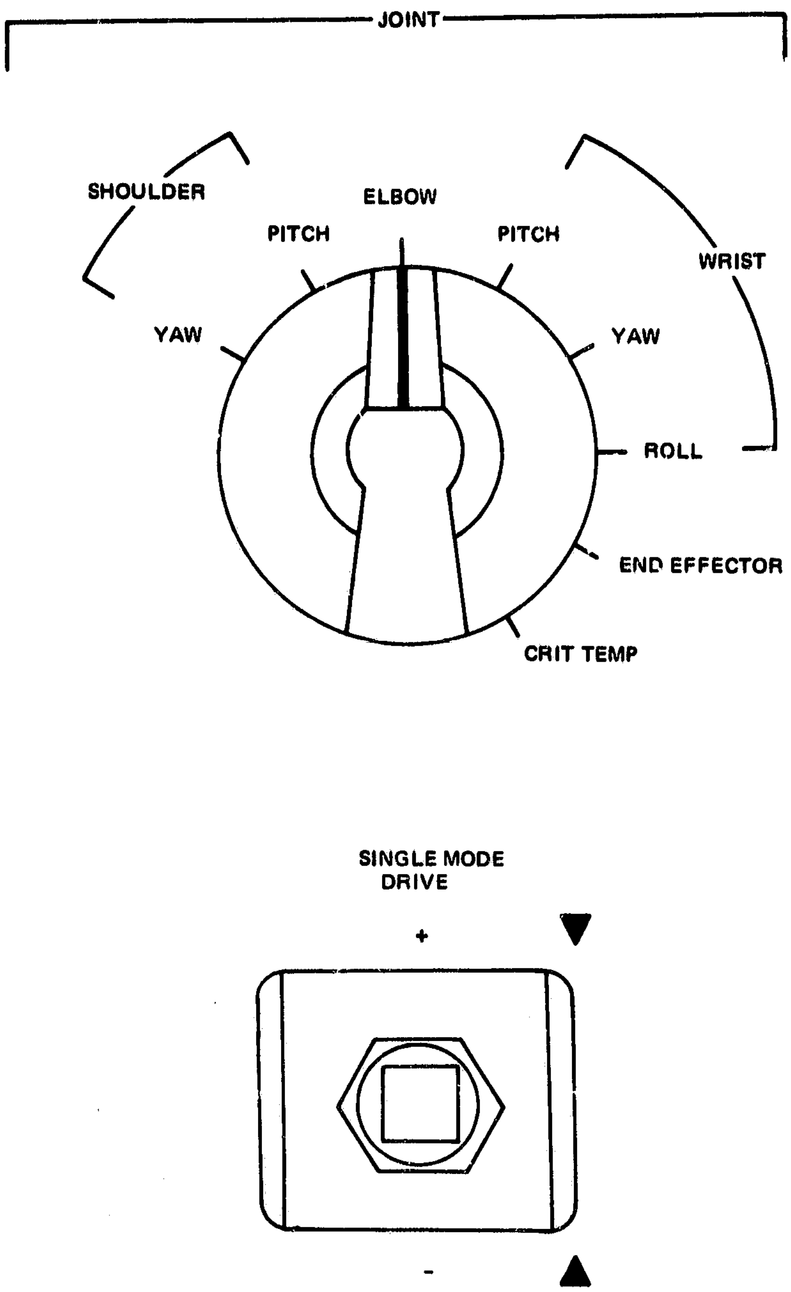

Figure 10. Joint Switches for Single-Drive Mode

TABLE 5

FORCE TORQUE CAPABILITY AND END EFFECTOR

	TORQUE RANGE (ft-lb)	FORCE (lb)	CONDITION
SHOULDER YAW	772-905	15.44-19.3	STRAIGHT ARM
SHOULDER PITCH	772-905	15.44-19.3	STRAIGHT ARM
ELBOW PITCH	528-660	18.41-22.76	BENT ARM OVERALL LENGTH $<$ 42 ft
WRIST PITCH	231-289	37.97-47.51	BENT ARM OVERALL LENGTH $<$ 20 ft
WRIST YAW	232-289	54.35-68.0	BENT ARM OVERALL LENGTH $<$ 14 ft
WRIST ROLL	231-289	–	

NOTE: ALL VALUES ARE QUOTES FOR THE ARM UNDER STEADY RIGID BODY STATIC CONDITION

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An initial assessment of these forces and the force an astronaut could exert (maximum 140 lbf) indicates the strength of the RMS is inadequate for this particular condition. Therefore, additional force reaction capability is required. This could be achieved by increasing the strength of the RMS or by providing reaction points on the structure being worked upon such that loads created by the astronaut are reacted back into the structure, thus off-loading the RMS.

1.1.7.1 Shuttle RMS Upgrading - A number of possibilities exist to increase the end point force of the RMS, including:

(1) Applying the drive train brakes in conjunction with the motors operating in a stalled condition.

(2) Increasing the stall torque capability of the motors.

(3) Incorporating a larger brake on the drive train.

(4) Incorporating a brake on the output side of the drive train.

Implementing (1), (2), and (3) has limited potential as each scheme is restrained by the joint gear train torque capacity. At best a 50% increase in force capability could be achieved but this would have major ramifications on RMS fatigue life such that the overall 100 mission capability of the RMS would be severely degraded.

Implementing (4) (i.e., overcoming the geartrain strength restriction) would require a major redesign of all joints on the RMS. In addition, the brakes would be extremely large (7000 ft-lbf on the shoulder joint). As such, this alternative does not appear to be a feasible solution.

1.1.7.2 Reacting Loads to the Space Structure - This would allow the Shuttle RMS to be used in an unmodified form. The configuration of reaction points is discussed in more detail in Paragraph 1.3.1.

1.1.7.3 Future Investigations - Due to the limited force capability of the Shuttle RMS and the problems associated with providing external reaction points (see paragraph 1.3.1), the possibilities offered by the torque capacity of the end effector should be investigated i.e., 230 ft-lbf is available at the end effector.

A study on methods to perform connecting and fastening operations utilizing torquing action should be performed at the earliest opportunity.

1.1.8 Obstacle Avoidance Approach

Obstacle avoidance is one of the most important areas that requires considerable development. Some of the possible approaches are:

- Completely automatic operation
- Manual operation with computer guidance
- Manual operation with computer caution and warning
- Manual operation.

Potential collisions may occur due to:

- The relative geometry of the manipulators, OCP, structural element being handled, Orbiter, and the structure being erected under normal circumstances
- Failures in Shuttle RMS.

The first step in successful implementation of obstacle/collision avoidance is a detailed study of the task to be performed. Taking the task of constructing Large Space Structure (LSS) platform as an example, the following steps are required:

- Identify all the steps involved in the construction
- Use scale models or computer models to determine the relative geometry between the various elements in the "construction site" during the construction process to determine potential conflicts in the form of obstacles
- Use scale models or computer models to determine the feasibility of avoiding conflicts (obstacles). If a procedure cannot be identified to eliminate all conflicts, construction is not possible with the chosen geometry.

The computer model used in the above study need not be a dynamic model. The model may be based purely on geometry and kinematics. The method of collision detection developed for the computer model can be used in the actual application with very little modification.

Based on the results of the task study performed, the various methods for obstacle avoidance can be developed and a comparative evaluation can be carried out to determine the best approach. Descriptions of various approaches follow.

1.1.8.1 Completely Automatic Operation - Except for the pickup and attachment of the structural elements to each other, operations such as:

- Moving beam elements after pickup from the beam builder to a location where the element is ready for attachment to the partically assembled structure

- Moving the OCP to the work center to enable the OCP operator to align and join the structural elements together

Can be performed in automatic mode. The above gross motion activities such as handling and transporting can be carried out using either a Record and Playback (RAP) mode or in a Real-Time Guidance (RTG) mode.

In the RTG mode, the trajectory is generated in real-time such that all obstacles are avoided during the execution. Such an approach requires the computer to maintain a model of all obstacles in the reach envelope of the manipulator. When the execution of the trajectory is in progress, at any instant of time, the required trajectory is generated such that the moving elements do not collide with the fixed elements in the operating envelope. The algorithms and software required for implementing the RTG mode is likely to be quite complex.

In the RAP mode, collisionless trajectories are generated using either scale models, computer models, or RTG software. The trajectories generated are stored in the on-board computer and played back when required.

In both RAP and RTG modes, the operator is provided with sufficient visual information to enable him to intervene and take over control manually in the event unexpected collisions are impending.

1.1.8.2 Manual Operation with Computer Guidance - The trajectories required for transport and handling operations are generated as in automatic operation, but the actual execution is carried out under manual control. The required trajectories may be generated either in the RAP mode or RTG mode. The information regarding the trajectory to be followed may be presented to the operator in the form of velocity components to be attained (thus specifying speed and direction of motion) or differential velocity components to be nulled, using the hand controllers. The display information may be presented to the operator either on the CCTV monitors or in the form of a heads-up display.

A similar concept can be used for assembly of structural elements provided that in place of the velocity components, the force/moment components required for assembly is presented for the assembly operation in progress. The operator attempts to match the displayed force/moment components using his hand controllers. The attained force/moment components are determined from measurements using a force/moment sensor mounted inboard of the manipulator end effector and are displayed alongside the required components. Alternatively, differential force/moment components may be presented to the operator, and he will attempt to null these using the hand controllers.

During the execution of the trajectory, the computer will keep track of the relative positions of the various elements to ensure the proper execution and warn the operator whenever deviations occur. The operator is provided with sufficient visual information to handle failure conditions.

1.1.8.3 Manual Operation with Computer Caution and Warning - The manipulator is under manual control from OCP or from aft crew station. The operator performs the transportation and handling tasks on the basis of direct views and visual information available through the CCTV system. The computer keeps track of the instantaneous relative locations of moving elements and fixed elements, as well as predicted relative locations at some future time (based on present rate of motion). The computer activates a caution annunciator and an audio alarm in the crew compartment and through the voice channel in the EVA suit whenever it is predicted that if the operator continues the present trajectory, a collision is likely to occur, and he has sufficient time to avoid collision by slowing down and by performing obstacle avoidance.

On the basis of the caution signal, the operator can perform obstacle avoidance. But if he fails to do so and if computer predicted that a collision is imminent and it can be avoided only through the immediate application of brakes, the computer activates the brakes, a warning annunciator, and an audio alarm.

1.1.8.4 Manual Operation - In normal operation, no computer assistance is provided for obstacle avoidance or collision avoidance. There is total dependence on available visual information and judgement and training of the operator.

1.1.8.5 Proximity Sensors - All schemes discussed earlier are based on predicted positions of moving elements in relation to fixed elements. The possibility of using point as well as distributed/area proximity sensors for collision and obstacle avoidance require careful evaluation and study.

1.1.9 Shuttle RMS Software Requirement

The present Shuttle RMS software does not perform collision/obstacle avoidance function. The baseline RMS software is quite adequate for OCP control functions because when OCP control is in effect, the OCP C&D is designated as the input location for the Shuttle RMS control in place of the Orbiter RMS C&D, through hardware switching. If parallel operation of OCP arm and a second arm is to be carried out, a second MCIU is required along with suitable modifications to the software with all routines coverted to re-entrant type. If OCP C&D is used to control the second arm, a line-of-sight coordinate system control function will be useful, and it can be implemented with a small increase in Shuttle RMS software (less than 100 words of memory).

Estimating the software required for collision/obstacle avoidance at this time is difficult because additional studies are required to determine the method of implementing collision/obstacle avoidance for OCP operations.

1.2 STRUCTURE

1.2.1 Fracture Mechanics Analysis

The effects of flaws and defects on the structure depend on a prior assessment of potential flaw sizes, types, and locations that can reasonably be expected to remain undetected by the best available NDE techniques. The degradation of the required service life of such initial flaws will be avoided by:

- Providing a flaw tolerant design
- Using the inherent fracture resistance of thin sheet materials such as 2024-T81 sheet or 2024-T851 plate. For example 2024-T81 sheet has a favorable ratio of plane stress fracture toughness (K_c = 55 ksi $\sqrt{\text{in}}$) to tensile yield strength (F_{ty} = 55 ksi)
- Designing for reduced stress levels in fracture critical areas
- Performing fracture mechanics analyses based on sustained and cyclic loads
- Carrying out fracture mechanics analyses on all pressurized tankage
- Establishing by analysis the proof test requirements.

1.2.2 One Man versus Two Man

1.2.2.1 Discussion - This issue is concerned with the number of astroworkers to be located on the OCP at one time. The trade is directed toward the practicality of more than one worker performing assembly or maintenance operations while fastened to a common base. Three open cabin platform tasks, utilizing the Multimission Modular Spacecraft (MMS), Large Space Structure (LSS), and Long Duration Exposure Facility (LDEF), are illustrated in Figure 11. The astroworkers are attached to the platform on turntables located 1.5 m apart. This provides adequate separation so that they would not impact one another while performing construction tasks. Maximum one-hand reach for each astroworker provides a total reach span of 4 m laterally and 1.45 m forward. Figure 12 contains Extravehicular Mobility Unit (EMU) reach data utilized in this analysis.

Figure 11 shows the relationship of one astroworker to the MMS module installation. The second astroworker cannot assist in this task. Another task shown is the installation or removal of a LDEF experiment tray. Screws are located on the periphery of the tray so during installation or removal the astroworkers could work in parallel. Joining of LSS beams is mainly accomplished by one astroworker. The

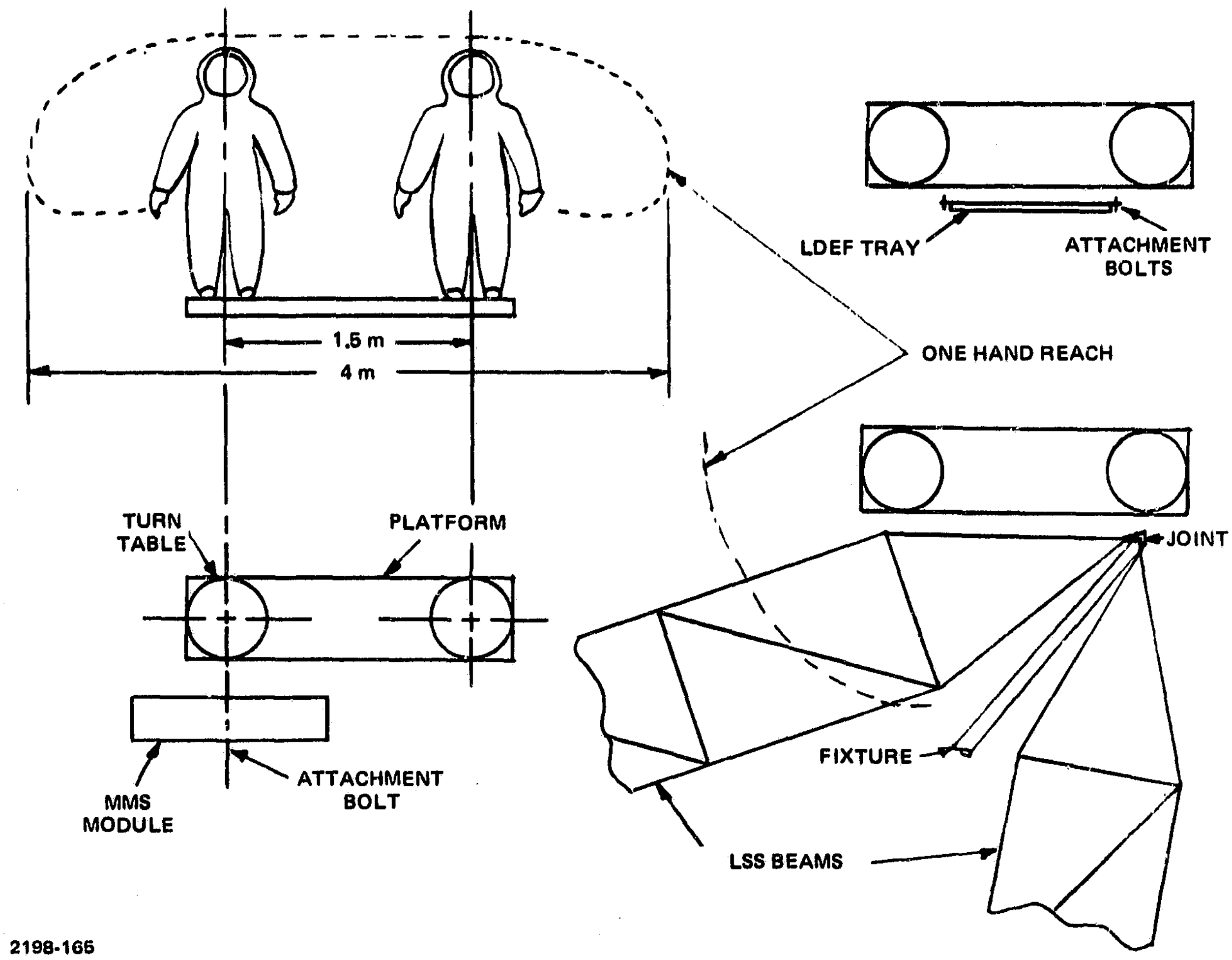
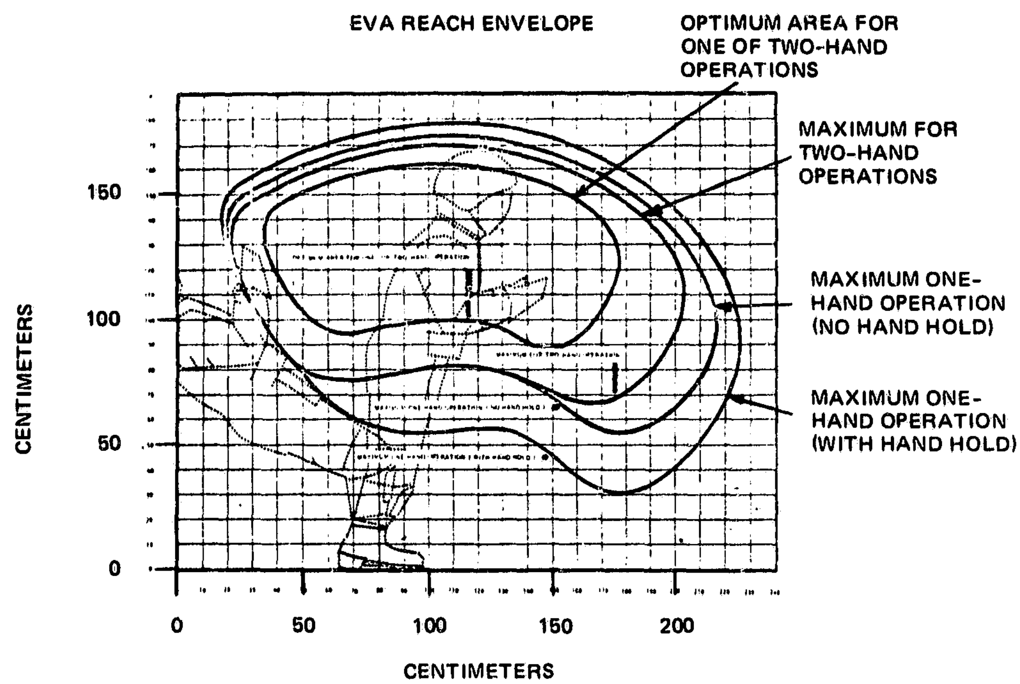


Figure 11. Two-Man Open Cabin Platform



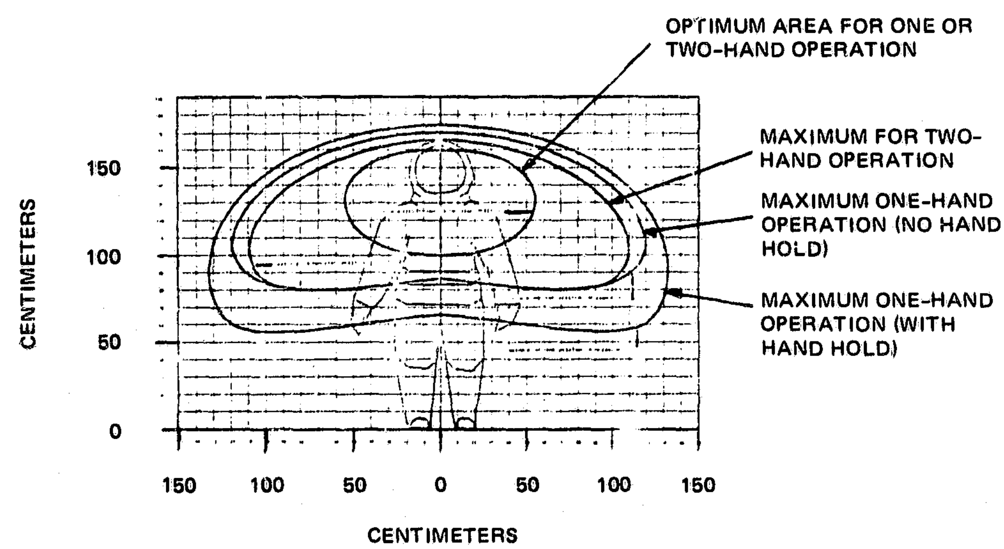


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Figure 12. Extravehicular Mobility Unit Reach Capability

second worker could steady the beam during joining operations; however, the main requirement is to have the opposite end of the beam positioned, a function well beyond the reach of an astroworker attached to a common platform.

1.2.2.2 Recommendations - The tasks discussed above and the majority of others, can be accomplished by one astroworker utilizing both hands, i.e., positioning a component and fastening it. A second astroworker's hands assisting in the same area may not be an advantage because only one person can use a specific tool at a time or work on a specific component. Because of the need to get close to the work, two people would tend to jostle one another when located too close together; in fact, they are more likely to hinder one another. Tasks that require a second astroworker usually need someone to position a component for assembly (e.g., beam end) and they are located some distance away from their co-worker. Control of the open cherry picker is a serial operation to assembly tasks; therefore a second astroworker could not improve this operation. Consequently, it is recommended that the open cherry picker concept provide accommodations for only one astroworker.

1.2.3 Design Loads

1.2.3.1 Requirements -

- Factors of safety
  - Primary Structure

    Yield Load = 1.2 x Limit load
    Ultimate Load = 1.5 x Limit load
  - Tankage
- Scatter factor = 4.0 on service life
- Service usage life = 10 yr.

1.2.3.2 Launch and Landing Operations Mounted in Orbiter Payload Bay -

- Design will comply with requirements of Payload Accommodation Document JSC 07700, Vol. XIV
- Because the load factors given in Table 7.11 of JSC 07700, Vol XIV, do not include the dynamic response of the payload, an estimate of design loads, based on analysis of similar shuttle payloads, must be made until detailed dynamic analyses are available. Table 6 summarizes design load factors for payloads on various shuttle missions. For initial MRWS design, the

TABLE 6

DESIGN LOAD FACTORS – SHUTTLE PAYLOADS (COMPARISON)

	LIFTOFF			LANDING		
JSC07700 (DOES NOT INCLUDE DYNAMIC RESPONSE OF THE PAYLOAD)	X Y Z	−0.1 +1.0 +1.5	-2.9 -1.0 -1.5	X Y Z	+ 1.0 + .5 + 2.8	−0.8 −0.5 +2.2
TEAL RUBY SPACECRAFT	X Y Z	+1.5 +2.5 +3.0	-4.5 -2.5 -3.0	X Y Z	+ 3.0 + 2.5 + 6.0	-3.0 -2.5 -4.0
OFT-4-PALLET MOUNTED EQUIPMENT GSFC S-420-3 & 8/78 (PRELIM)	X Y Z	+0.4 +3.3 +3.1	-4.5 -3.3 -3.5	X Y Z	+ 2.5 + 2.5 + 6.5	-2.5 -2.5 -2.6
IUS MOUNTED PAYLOADS PAYLOAD WGT = 2000 lb	X Y Z	+1.5 +2.0 +4.5	-4.5 -2.0 -4.5	X Y Z	+ 4.5 + 4.0 +10.0	-4.5 -4.0 -8.0
PAYLOAD WHT = 13,000 lb SS-STS-100-JAN 15, 1976	X Y Z	+1.0 +1.5 +3.5	-4.0 -1.5 -3.5	X Y Z	+ 3.0 + 2.0 + 5	-3.0 -2.0 -3.0

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load factors of the Teal Ruby spacecraft were chosen as a first estimate for liftoff and landing loads. These factors will be used for initial sizing and must be verified by a detailed dynamic analysis.

1.2.3.3 Space Operations Loads -

- Loads induced by RMS/robust arm motions TBD
- Equipment handling TBD.

1.2.3.4 Materials - The various materials applications will be selected for structural efficiency, outgassing and flammability criteria, and other environmental requirements.

1.2.4 Service Fatigue Life

The fatigue life of the cherry picker structure should be assessed for service usage of 10 yr with a scatter factor of 4.0. The structure will be a safe-life design with incorporation of fail safe features by providing adequate fracture-arrest capability and residual strength in any potential damaged condition. The fatigue spectra should apply external load cycles which may be experienced during the life of the cherry picker. The fatigue analysis will be carried out on various methods of construction to obtain the most efficient structure that will meet the requirements.

1.3 MECHANICAL

1.3.1 Stabilizer Single Point versus Multipoint Attachment

Because of the limited force reaction capability of the Shuttle RMS in comparison with the maximum of 140 lbf the astronaut is capable of exerting, it is necessary to consider other methods of reacting these forces.

Only the cases of structures attached to the Shuttle are considered. If work is to be performed on a free-flying structure, it is necessary that the astronaut exerts no net forces or torques on the structure.

Generalized Loading Conditions

When working in the cherry picker, it is assumed that the astronaut can exert one or all of the loads shown in Figure 13.

One-Point Support - To react the loads, the reaction point must supply equal and opposite forces and moments. However, the reaction moments will be greater than the applied moments due to the effects of the offset (l and h) of the forces $F_{x,y,z}$ about the reaction point.

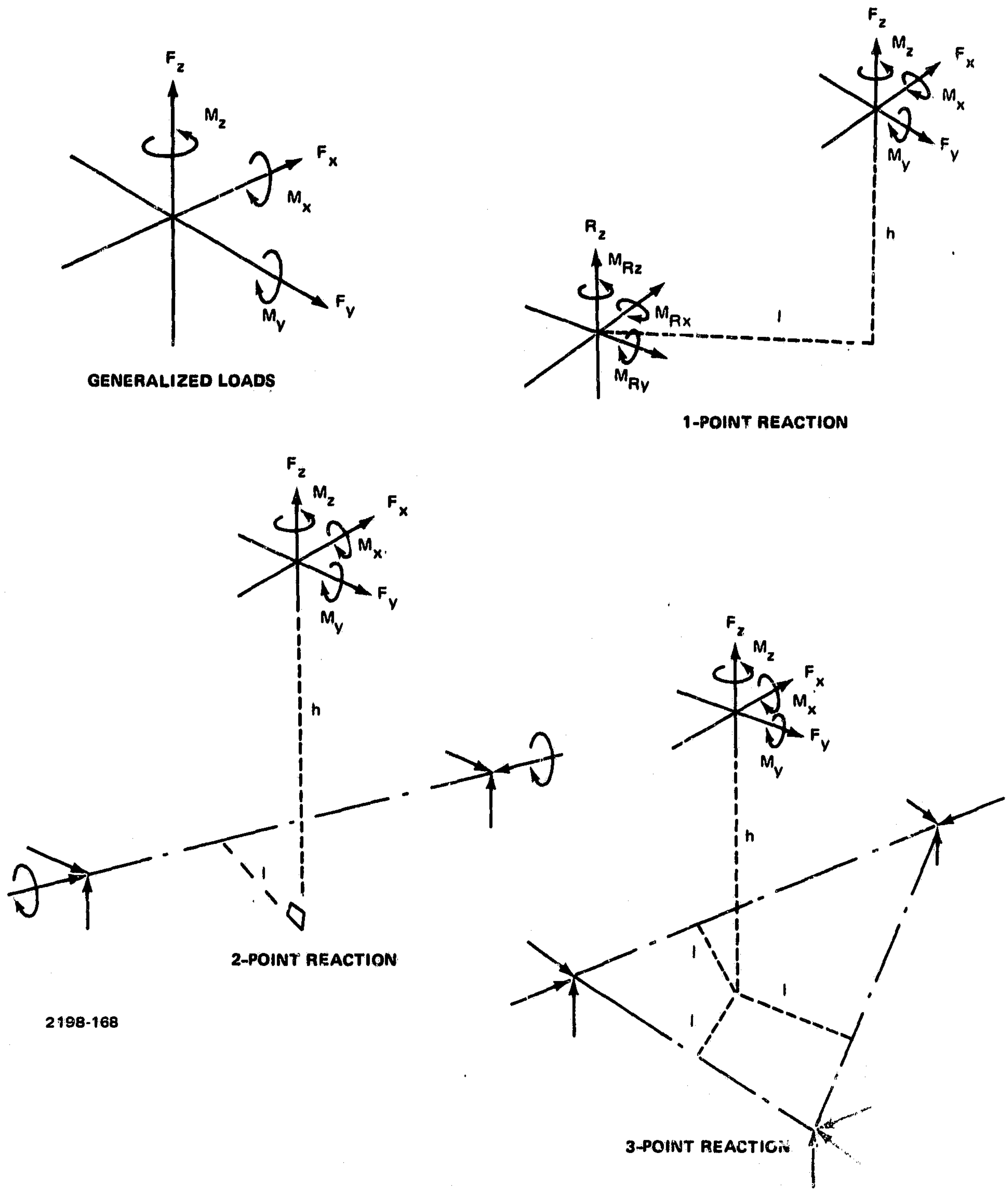

Figure 13. Methods of Reacting Astronaut Forces

Two-Point Support - A two-point reaction system reduces the requirements of the reaction points. Only one moment is required and the magnitude of the reaction forces are reduced because of load sharing between the reaction points.

Three-Point Support - The reactions of a three-point support system are required to supply three reaction forces (provided the reaction points encompass the loading point). The magnitude of the loads could be less than those for the one- and two-point systems. An advantage of this system is that no reactive moments are required.

Selection of Reaction System

The choice of reaction system will depend on the ease of implementing each system and the load bearing capabilities of the structure.. For the case of the open cherry picker, the most straightforward approach would be for the astronaut to hold the structure on which he is working, thus reacting any loads he generates back into the structure via his own body.

For operations where this is not possible (e.g., a closed cabin cherry picker), mechanical means to react the loads will be required. Choice of a one-, two-, or three-point system will require further investigation into the relative merits of each system. Factors to be considered include:

- Complexity of single-point versus multipoint grappler systems
- Provision of grapple points on the structure
- Access to the work point.

The possibility of utilizing the torque capability of the Shuttle RMS should be investigated. That is, can a screwing action, rather than a direct force action, be used by the astronaut to perform the various tasks associated with the cherry picker? If this were possible, the need for external grapple points would be obviated.

A single stabilizer is preferred for the reasons that are summarized in Table 7 and elaborated in greater detail in Paragraph 2.3.7 (closed cabin cherry picker). However, some of the arguments are more powerful when applied to the open cherry picker. These are expanded here.

The dextrous arms of a closed cherry picker limit the amount of force an operator can transmit to a worksite. This is not true of an open cherry picker. Here, an operator can develop forces of 140 lb in any direction. Because these forces will induce large bending moments at worksites, strong stabilizer lugs are required. Consequently,

TABLE 7
ONE VERSUS THREE STABILIZERS

SINGLE STABILIZER	THREE STABILIZERS
• LOWER GRAPPLE COST • LOWER GRAPPLE WEIGHT • LOWER MRWS COST AND WEIGHT • HIGHER PRODUCTIVITY – REDUCED BERTHING TIME – LARGER WORKING VOLUME – BETTER WORKSITE ACCESS	• HIGHEST TORQUE INPUT TO WORKSITE

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the open cherry picker will not stabilize to fragile structure. All work which requires stabilizing will be performed at a worksite with a single lug.

To utilize a three stabilizer system which does not apply moments to the worksite structure, the stabilizer should enclose the work zone. This implies that one stabilizer should be above the astronaut's head. But no structure exits there on an open cherry picker. Consequently, the three stabilizer arrangement would add significantly to the cost and weight of an open cherry picker.

1.3.2 Rate Command versus BFR Stabilizer

The choice between rate controlled versus bilateral force reflecting (BFR) stabilizer depends primarily on the function of the stabilizer. If the stabilizer is to perform assembly and joining operations, force feedback becomes essential and BFR has a clear advantage. Because assembly-type operations will be performed by the man in the open cherry picker, the function of the stabilizer is primarily holding and transporting structural elements and modules. Consequently, the stabilizer can be a rate-controlled device with simple controllers and geometry. A stabilizer with passive joints and brakes can also be considered as an alternative. In this case, the OCP operator will release the brakes, move the grappler manually to the required position, and apply the brakes to hold the stabilizer in place.

The factors to be considered in the case of a rate commanded stabilizer are:

- Simple controllers which are compact
- No force feedback
- Stabilizer geometry can be simple, thus requiring no resolution of rates
- The stabilizer joint drives can be simple (if open-loop control is adopted), containing only motors and brakes
- Simple system which is compatible with OCP concept.

The factors to be considered in the case of BFR stabilizer are:

- Complex controller requiring position controlled servos in all joints containing motor, brake, position sensor, and tachometer
- Controller large and may not be compatible with OCP dimensions and layout
- Effective force feedback, and consequently, if joining operations are to be performed using stabilizer, BFR has an overriding advantage over rate control with no force feedback

- The stabilizer joints require position controller servos containing motor, brake, position sensor, and tachometer
- Complex system which may not be compatible with OCP concept
- Difficult to operate for a suited operator.

In view of the above factors, the tentative choice is a rate-controlled stabilizer. Further study is recommended to determine the tasks to be performed by the stabilizer and the performance requirements to make a final choice.

1.3.3 Stabilizer Design Conditions

Figure 14 shows the concept for a 3 degrees-of-freedom (DOF) electromechanical manipulator which is attached to the bottom of the OCP and is used to grasp a portion of the worksite as a stabilizing device.

The link attached to the OCP is driven ±90° in yaw, parallel to the astronaut's platform. The second link is driven 270° in pitch to permit horizontal positioning under the platform, for Shuttle Bay Storage, and up to a vertical orientation in front of the astronaut for end effector installation or removal. This link incorporates a powered extension of 16 in. The end of this link is compatible for the attachment of a family of end effectors. Two such effectors are shown: one to pick up pipes between 1 to 4 in. in diameter and another to pick up triangular trusses between 0.5 to 1 m on a side. The end-effectors are stowed under the platform when not in use.

Table 8 specifies the minimum design requirements for the stabilizer system:

- One stabilizer satisfies the results of a previous tradeoff study on the use of multistabilizers
- Open loop-type control used for end effector grip and for each DOF is controlled by individual two-position hold/neutral switches located on the OCP control console
- The length designated reflects the pipe end effector configuration. Each end effector design will impact the overall length and must be considered to ensure the astronaut is within reach of the worksite task.

The pros and cons of 3 DOF stabilizer are:

- Disadvantages
  - Limited DOF restricts orientation and or crewman's reach to worksite unless specific stabilization points are provided

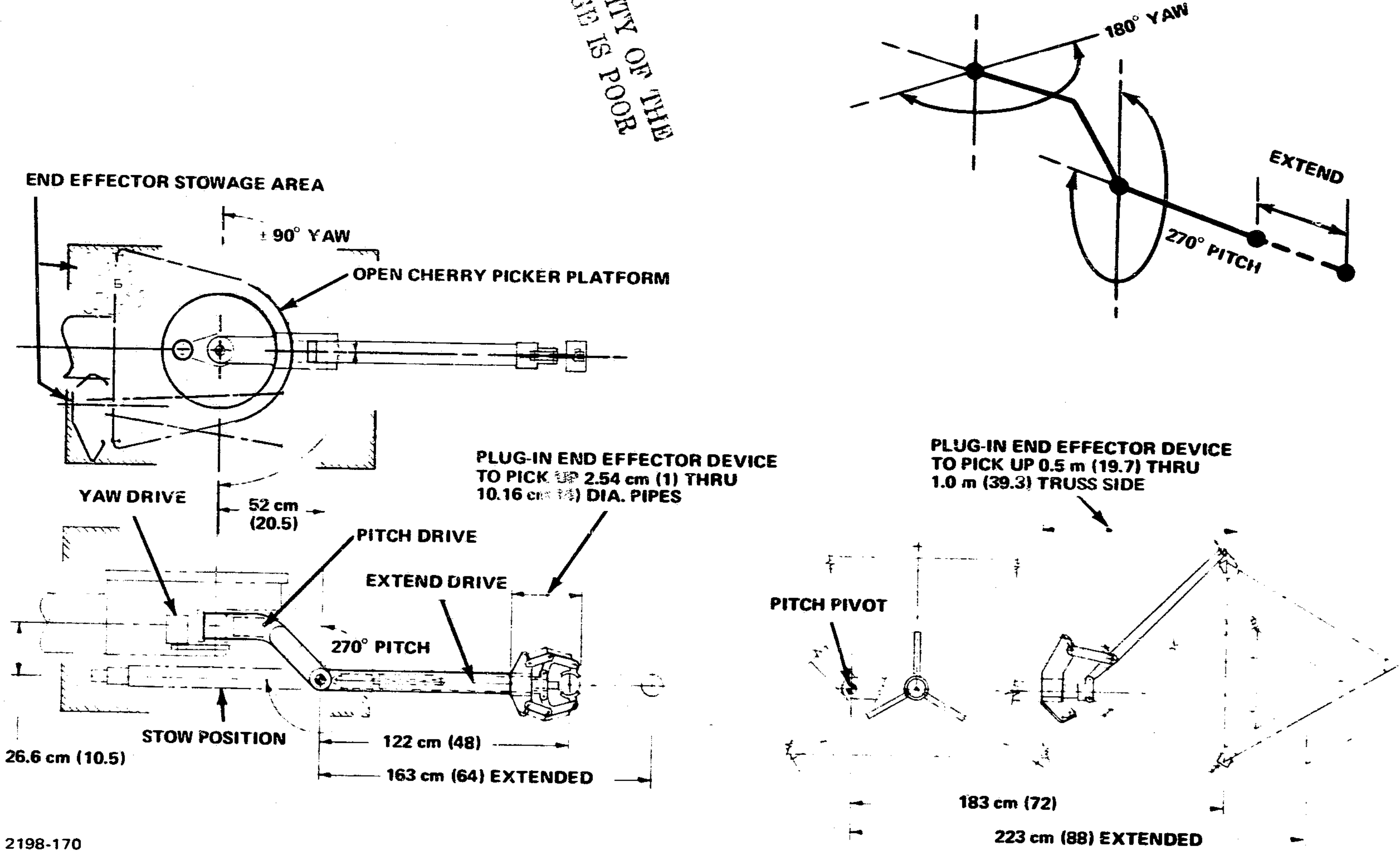

Figure 14. Three-Degree-of-Freedom Stabilizer

TABLE 8

TYPICAL STABILIZER SYSTEM

• NUMBER OF STABILIZERS	1
• TYPE OF CONTROL	OPEN LOOP
• CONTROL DEVICE	DOF SWITCHES (TWO POSITION HOLD/ NEUTRAL)
• LENGTH	1.2 TO 1.6 m
• DEGREES OF FREEDOM (DOF)	3
• DEXTERITY	S (Y) E (P) W (E)
• MAX TIP FORCE (LOCKED)	40 lb
• MAX TIP MOMENT (LOCKED)	≈ 4000 in.-lb
• ACCURACY/RESOLUTION	± 1 cm/± 2 mm
• STABILIZER ARRANGEMENT	
– POWER	ELECTROMECHANICAL
– TRANSMISSION	PROXIMITY DRIVE
– COUNTERWEIGHTS	NO
• FAIL-SAFE LOCKS AT POWER LOSS	YES

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- Stowing requirements and DOF limits reach capability range (short-to-long)
- Stowing end effectors increases crewman tasks
- Not an off-the-shelf item

● Advantages

- Plug-in end effector concept provides wide range of pickup capabilities and force distribution
- Low number of actuators - 3 motion 1 grip against 6 motion 1 grip.

It should be noted, that even with the additional DOF provided by the RMS, these DOF are not wholly additive to the 3 DOF stabilizer because the DOF that are important are those relative to the astronaut's worksite and the stabilizer end effector.

A properly configured 6 DOF device would eliminate the disadvantages stated, due to its ability to orient the end effector to any position on the worksite. To accomplish the same degree of capability with a 3 DOF device would require specifically designed, single or multiple pickup points.

It is recommended that the concept of a family of end effectors be used to enhance a wide range of pickup capability and force distribution with a 6 DOF manipulator.

1.3.4 Payload Handling

The MRWS Open Cherry Picker (OCP) is used to support the spacecraft servicing and construction operations of near-term missions. These missions require the EVA crewman working in the OCP to handle large, bulky subsystem modules and equipments. Table 9 lists the size and mass of the equipments for the near-term missions. The OCP should provide a handling device to assist the crewman in the transportation and installation of the spacecraft equipment.

1.3.4.1 Design Approach - A concept for a payload handling device needed in servicing the Multimission Modular Spacecraft (MMS) is shown in Figure 15. The OCP would be equipped with two of these handling devices, one for the replacement module that is retrieved from the orbiter cargo bay and the other to handle the spent spacecraft module. Once the OCP is positioned at the spacecraft, the EVA crewman removes the spacecraft subsystem module using a special removal/install tool which is stowed aboard the OCP. The spent module is placed on the pedestal of the handling device and the upper clamps secured to the module. The special removal/install tool is then released from the module, and the spent module is then moved to the stow area by

TABLE 9

SPACECRAFT EQUIPMENT TO BE HANDLED BY MRWS OCP – NEAR-TERM MISSIONS

MISSION	EQUIPMENT	MASS (kg)	SIZE, m (L X W X H)
LSS	LARGE FORMAT CAMERA (LGC)	181	2.9 X 0.91 X 1.7
	SHUTTLE IMAGING RADAR–A (SIR–A)	90 135 55	2.2 X 0.15 X 9.4 1 x 0.25 X 1.5 0.5 X 0.6 X 0.6
	SHUTTLE MULTI-SPECTRAL IR RADIOMETER (SMIRR)	70	0.8 X 0.7 X 0.85
	OCEAN COLOR EXPERIMENT (OCE)	94	0.79 X 0.27 X 0.24 0.43 X 0.30 X 0.53 0.48 X 0.17 X 0.22
	STANDARD OZONE SOUNDING UNIT (SOSU)	20 20	0.33 X 0.15 X 0.2 0.33 X 0.15 X 0.2
	MEASUREMENT OF AIR POLLUTION FROM SATELLITE EXPERIMENT (MAPS)	63 1	0.75 X 0.75 X 0.45 0.1 X 0.15 X 0.1
	MATERIAL EXPERIMENTS ASSEMBLY (MEA)	685	1.9 X 0.96 X 1.1
MMS	POWER MOUDLE	158	1.2 X 1.2 X 0.46
	ACS MODULE	167	1.2 X 1.2 X 0.46
	C&DH MODULE	97	1.2 X 1.2 X 0.46
LDEF	PERIPHERAL EXPERIMENT TRAYS	82	0.84 X 1.2 X 0.3
	END EXPERIMENT TRAYS	91	78 X 0.85 X 0.46

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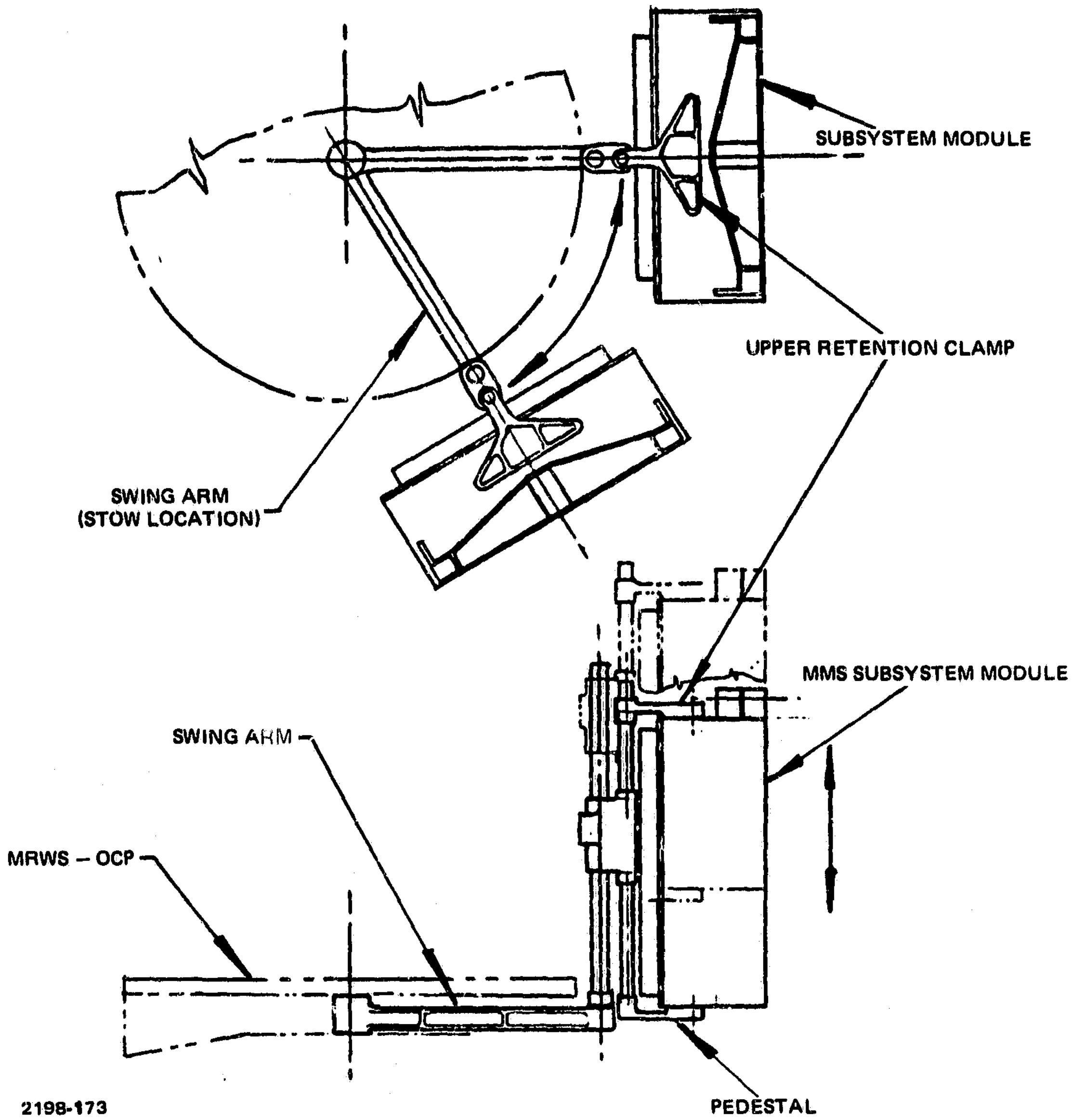


Figure 15. Mission Peculiar Handling Device MRWS OCP -- MMS Servicing Mission

means of the handling device swing arm. The replacement subsystem module is brought into place using a second retention/stow device and the reverse procedure is followed to install the new module.

Similar handling devices are required for removal and installation of the experiment trays used on the Long Duration Experiment Facility (LDEF) as well as the sensor installations required in the construction of the Large Space Structure (LSS) platform.

1.3.4.2 Required Simulation Analysis - Simulations of the OCP servicing and construction tasks requiring the use of identified mission peculiar handling equipment should be performed, and the EVA crewman/device interfaces evaluated and verified as well as the handling device/equipment interfaces.

1.4 ENVIRONMENTAL CONTROL AND LIFE SUPPORT

Extravehicular Mobility Unit

The open cherry picker will require use of pressurized suits. Because the use of gas umbilical connections from the fixed base to the cherry picker is considered to be impractical, the pressure-suit configurations were limited to three candidates per Figure 16.

Concept 1 is based on state-of-the-art EVA backpacks. Crew mobility and consumables redundancy is limited (30 min provisions per 8-hr shift).

Concept 2 is based on a two-section suit pack (backpack plus carry-on). Mobility is classed as acceptable, based on provisions for optional location of the carry-on pack during MRWS ingress/egress, (possibly strapped to crew leg). Redundancy of consumables is good based on stowage of one extra carry-on pack aboard the MRWS.

Concept 3 is similar to Concept 2 except that the carry-on pack is replaced by serviceable stores aboard the MRWS. Although the mobility rating of Concept 3 is good, the logistics of MRWS consumables resupply and the necessity of routine umbilical reconnection in the MRWS are undesirable.

The standard STS pressure suit, which includes all services in a self-contained backpack (Concept 1) is adequate for EVA in the open cherry picker and imposes no new development costs. Concepts 2 and 3 provide better mobility and redundancy than the standard suit, but introduce additional suit development or MRWS design complications.

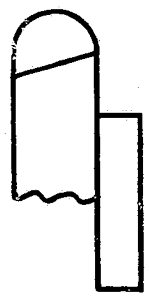
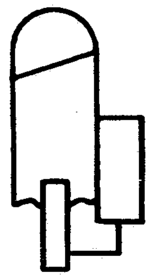
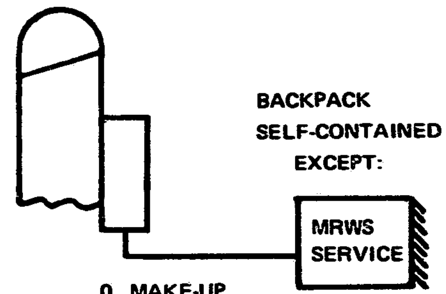
CONCEPT 1	CONCEPT 2	CONCEPT 3
		
BACKPACK SELF-CONTAINED	BACKPACK SELF-CONTAINED EXCEPT: CARRY-ON PACK 0_2 MAKE-UP COOLING (SUBL) POWER (BATT)	BACKPACK SELF-CONTAINED EXCEPT: 0_2 MAKE-UP COOLING (SUBL) POWER (BATT)
BACKPACK VOLUME: 3.3 ft^3 BACKPACK WEIGHT: 149 lb	BACKPACK VOLUME: 2.0 ft^3 BACKPACK WEIGHT: 63 lb CARRY-ON PACK VOL: 1.5 ft^3 CARRY-ON PACK WT: 102 lb	BACKPACK VOLUME: 2.0 ft^3 BACKPACK WEIGHT: 63 lb CARRY-ON (HOSE) VOL: 0.1 ft^3 CARRY-ON (HOSE) WT: 8 lb
MOBILITY: IN MRWS – ACCEPTABLE ACCESS TUNNEL – POOR	MOBILITY: IN MRWS – GOOD ACCESS TUNNEL – ACCEPTABLE	MOBILITY: IN MRWS – GOOD ACCESS TUNNEL – GOOD
VEHICLE INTERFACE: NONE	VEHICLE INTERFACE: STORE CARRY-ON PACK	VEHICLE INTERFACE: PLUG-IN TO MRWS SERVICE
HARDWARE STATUS: CURRENTLY AVAILABLE	HARDWARE STATUS: PACKAGE DEFINITION TBD	HARDWARE STATUS: PACKAGE DEFINITION TBD
REDUNDANCY: LIMITED TO BACKPACK CAPACITY	REDUNDANCY: ADDITIONAL CARRY-ON PACK CAN BE STOWED ON MRWS	REDUNDANCY: UNLIMITED MRWS SERVICE
(REF HAM STANDARD)		

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Figure 16. MRWS Open Cherry Picker (Pressure Suit; 8-Hour Shift)

1.5 CONTROLS AND DISPLAYS

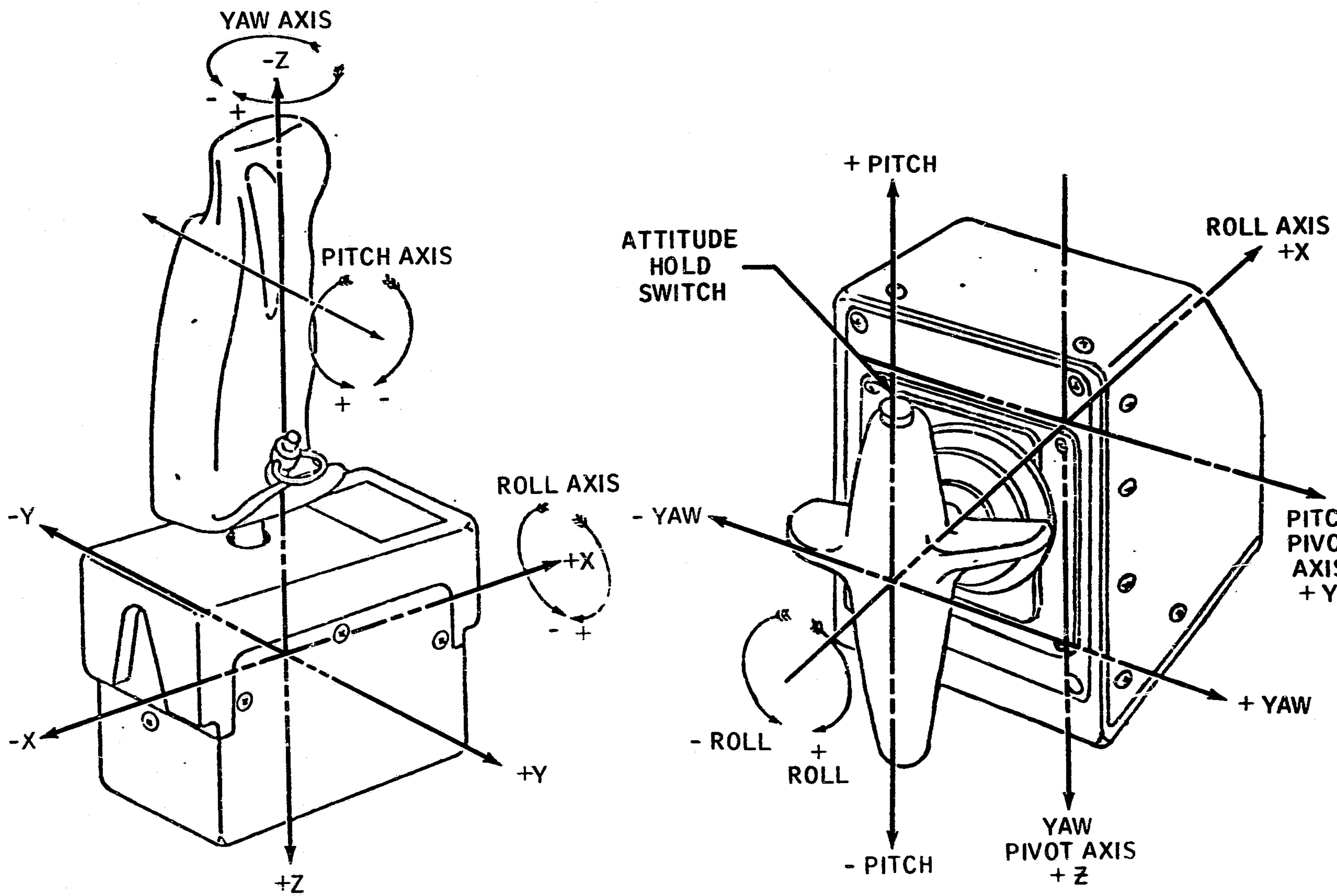
1.5.1 RMS Controller

For near team mission the MRWS Open Cherry Picker (OCP) utilizes the Shuttle Remote Manipulator System (RMS) as the arm component in the OCP configuration. The OCP is mounted at the end of the 15 meter long RMS and should provide the EVA crewman hand controller(s) which control the six degrees of motion of the RMS. The RMS is normally controlled from the Shuttle Payload Specialists Station (PSS), but for OCP operations the OCP controller is interfaced with the PSS and should be provided with an override feature.

In the mid term mission for the deployment and assembly of microwave antenna development article (TA-1) and photovoltaic SPS development article (TA-2) two cranes mounted on a crane turret operate from the Space Construction Module (SCM). One crane moves the payloads and the other crane supports an EVA crewman in an open cab cherry picker MRWS. The OCP mounted at the end of the 35 meter long "C.P." crane arm should provide hand controller(s) which control the seven degrees of motion of the C.P. crane. The EVA crewman working from the OCP is always in close proximity to the work area and he should also be provided with over-riding control capability of the "payload" crane when close-in payload movements are required.

1.5.1.1 Design Approaches - Qualified and developmental translation and rotation hand controllers exist from Apollo, Skylab and Shuttle programs. These controllers can be considered for use on the OCP. Figure 17 illustrates a comparison of Apollo type rotational hand controller used for Skylab and a controller developed for the Manned Maneuvering Unit (MMU). The Apollo type controller has a pistol grip handle which provides the control authority for the pitch, roll and yaw axes. The MMU controller employs a T-handle to provide for three axis control. Another consideration is the Orbiter RMS hand controllers that are operated at the aft flight crew station. Also switches could be utilized to control each axis of motion. These could be on-off or proportional lever controllers.

1.5.1.2 Selected Hand Controllers - The translation and rotation hand grips developed for the MMU shown in Figure 18 and the mechanical/electrical layout of the RMS controllers are selected as the baseline controls for the MRWS open cherry picker. The MMU controllers are designed to interface with the crewman's Extravehicular Mobility Unit (EMU) gloved hand and their small size will help minimize the OCP



APPOLLO TYPE USED ON SKYLAB

MMU

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Figure 17. Rotational Hand Controller Comparison

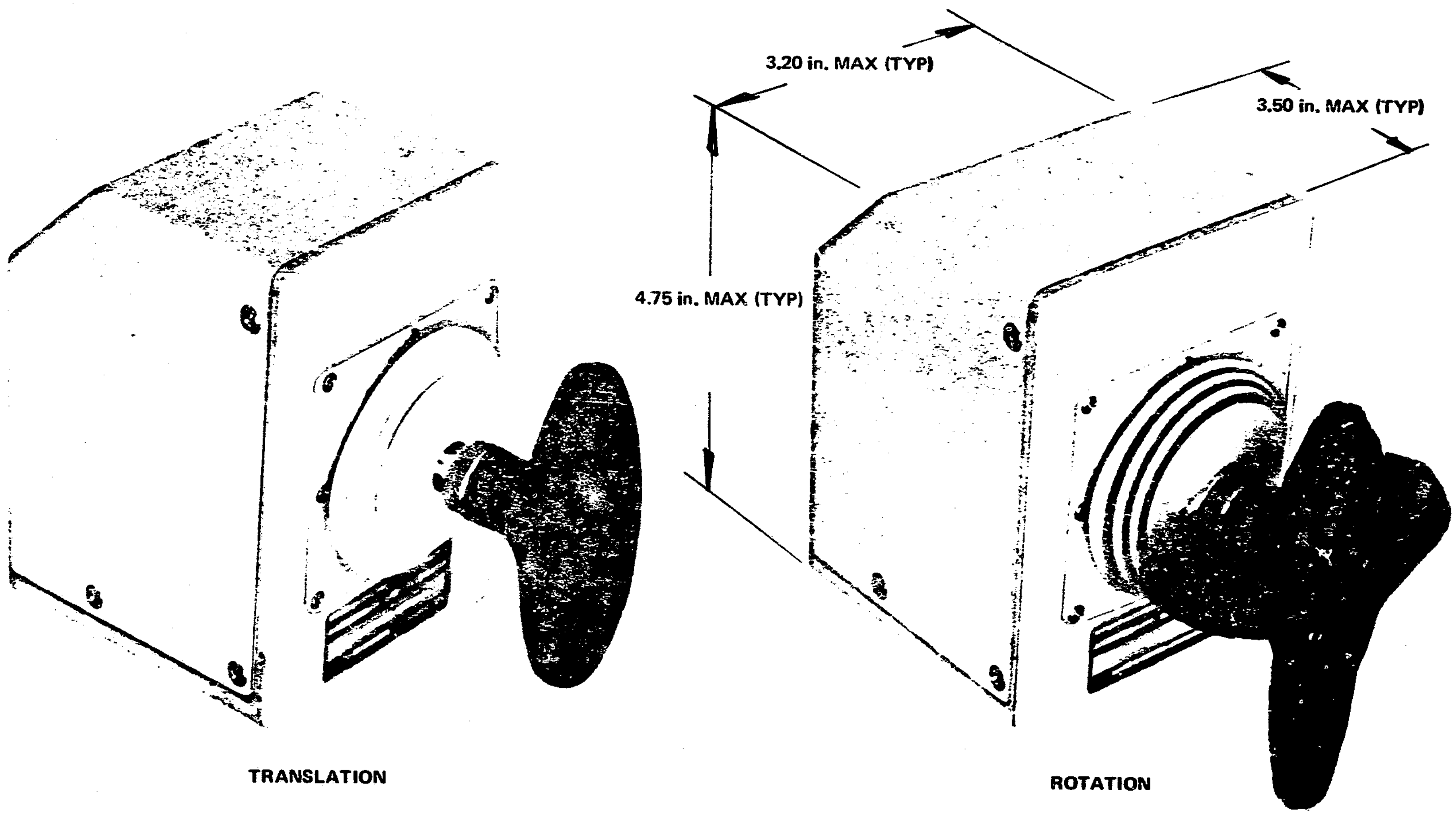

Figure 13. MMU Developmental Hand Controllers

console required. Selection of the RMS mechanical/electrical components will minimize design modifications.

1.5.1.3 Required Simulation Analysis - Location of the OCP control console and position of the hand controllers are issues to be evaluated. The relationship of the control console and the EVA crewman's position on the OCP is important to his ability to maneuver the OCP to and from the required work sites. Forward, aft and side mounted control stations should be evaluated on the OCP simulator.

1.5.2 Control/Display Panel Arrangement

It is proposed that wherever possible the control and displays will be similar to those used in the Orbiter (Figure 19). However, as discussed in Paragraph 1.1.6, most of the Orbiter C&D panel parameters are not required at the cherry picker.

No mode control is required as manual augmented mode is selected automatically when the cherry picker control station is selected. Similarly, there is no requirement for backup control, end effector controls, or single/direct drive. It must also be taken into account that the cherry picker operator will be in his EVA suit and the operation of switches will be more difficult.

It is proposed, therefore, that a very simple C&D panel, which will contain only cautions together with a brake command switch, be implemented on the cherry picker C&D panel for RMS control. If control of the other arm is required, then a Port or Starboard power selection switch will be required.

The hand controllers will have the same function as the Rotational Hand Controller and Translational Hand Controller in the Orbiter, but the movement and force characteristics will require an increase as the cherry picker operator will be constrained by his bulky EVA suit.

A minimum C&D panel is shown in Figure 20. If a TV monitor is required for control of the other arm from the cherry picker, then it would be possible to use the TV screen to display the cautions (Table 10).

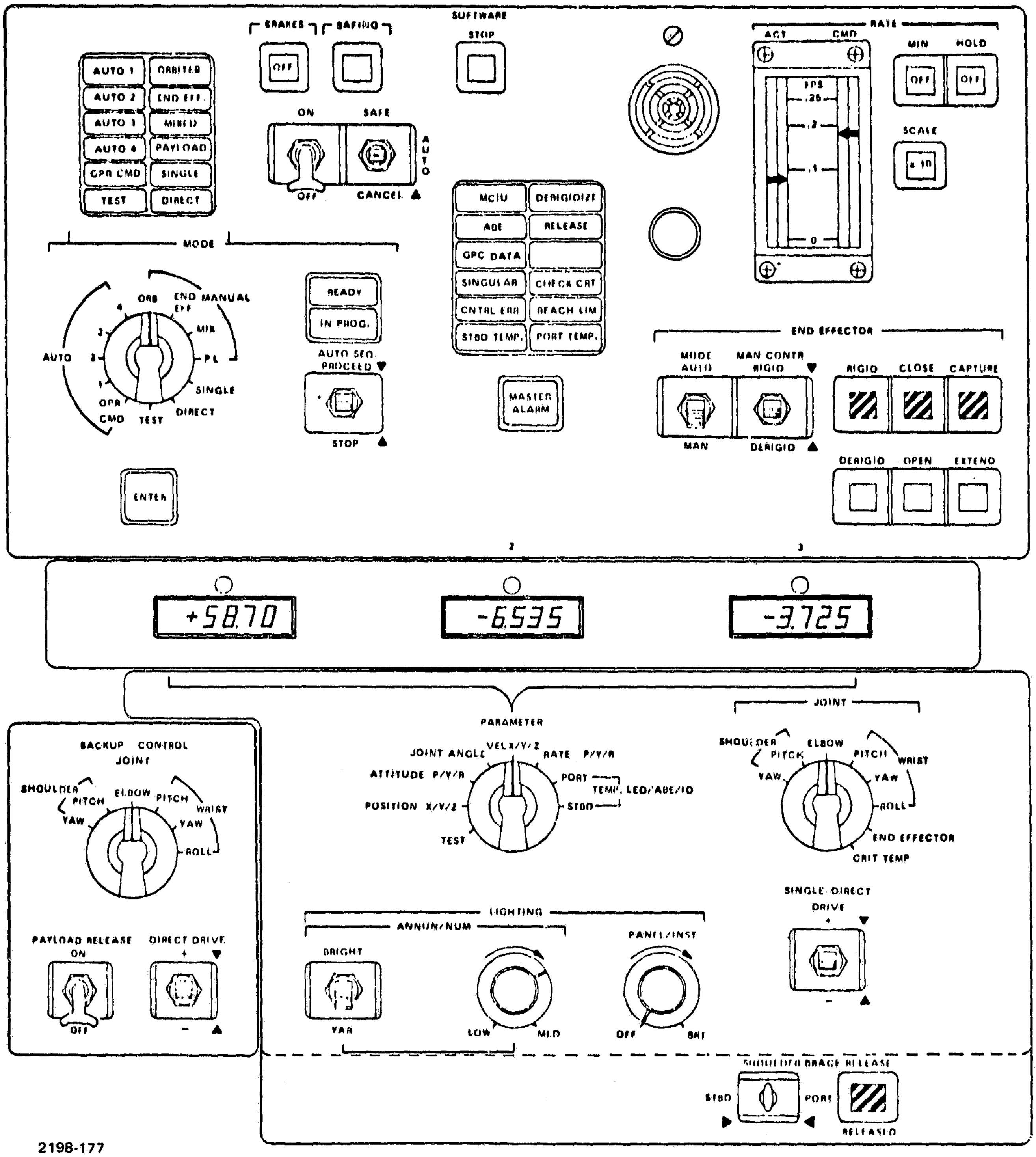

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Figure 19. Orbiter Displays and Controls Panel

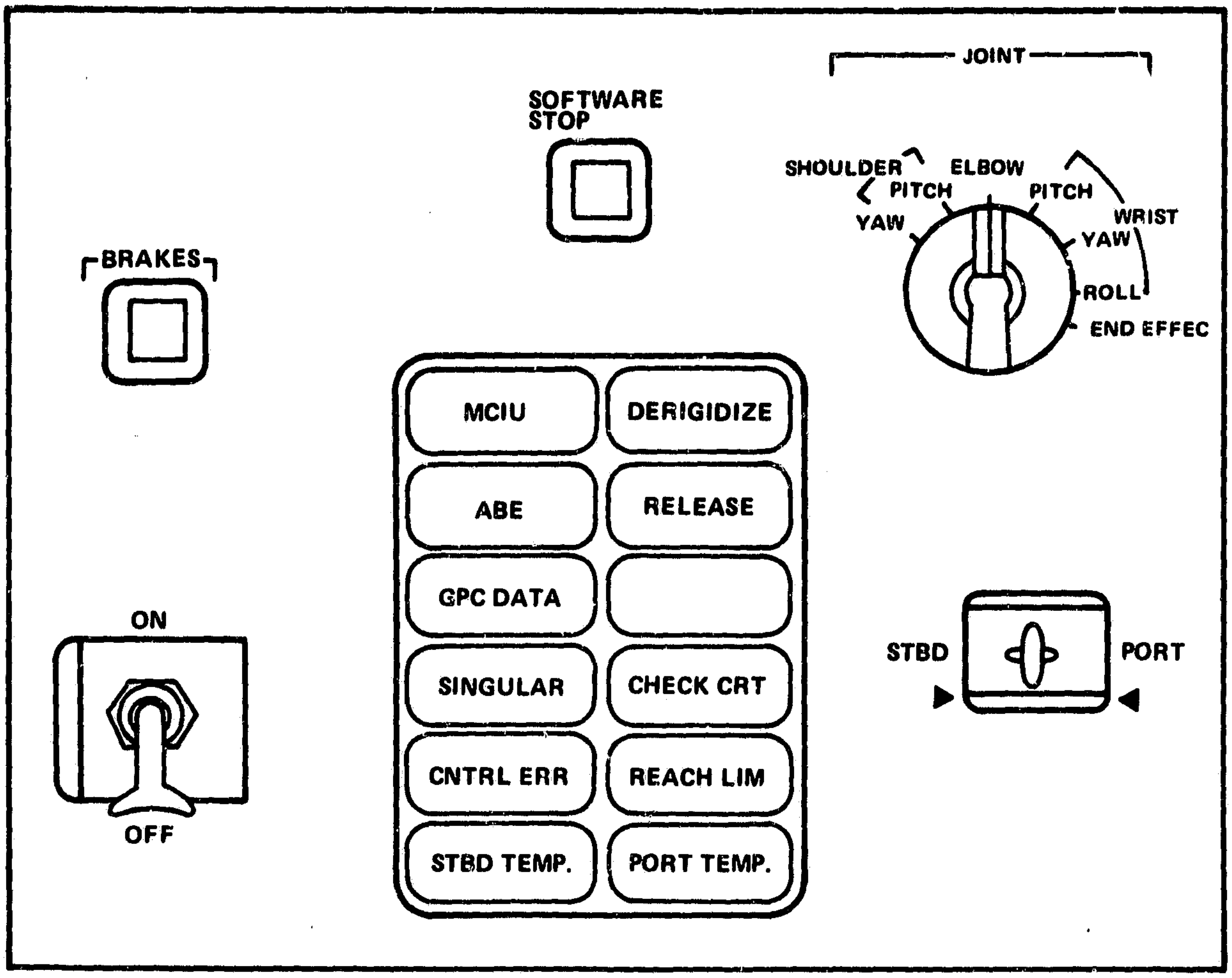

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Figure 20. Open Cherry Picker - Controls and Displays Panel (Simple)

TABLE 10

CONTROLS AND DISPLAYS

METHOD OF MONITORING	ADVANTAGES	DISADVANTAGES
SIMPLIFIED ORBITER DISPLAYS AND CONTROLS PANEL	– OPERATOR FULLY FAMILIAR NO RETRAINING NECESSARY – DATA ALREADY IN FORMAT THAT IS SUITABLE – MAKES USE OF DATA TRANSMISSION SYSTEM BETWEEN ORBITER D&C AND MCIU NO SEPARATE SYSTEM REQUIRED – HARDWARE DESIGNED	– NO EXTENSION OF DISPLAYS POSSIBLE WITHOUT CONSIDERABLE HARDWARE CHANGES
CRT DISPLAY	– EASILY EXTENDED – COULD BE USED AS TELEVISION MONITOR IN ADDITION TO DISPLAY	– REQUIRES NEW INTERFACE AND CONDITIONING ELECTRONICS – RETRAINING OF OPERATOR – INCREASE IN POWER REQUIREMENT

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1.5.3 Stabilizer Controller

To reduce the size and cost of the MRWS, the stabilizer will use the same control devices that are used to position the open cherry picker -- two RMS hand controllers with MMU hand grips which provide rate control. A mode switch on the control console will be used to replace cherry picker control with stabilizer control and vice versa.

1.6 ELECTRICAL POWER

Orbiter Umbilical versus Self-Contained Power Source

Additional power for the cherry picker in excess of that capable of being supplied through existing Shuttle RMS cables may be derived in two ways:

- Self-contained power supply in the cherry picker
- Umbilical cable from the orbiter to the cherry picker.

The amount of additional power required to operate the cherry picker would be the same for either method (neglecting small losses in cable).

A disadvantage of a self-contained power supply is that it would be necessary to have builtin redundancy in case of failure; if the orbiter supplies were used, this redundancy would already be included.

A disadvantage of the umbilical cable is the extra weight of the cable, the complexity of installing an extra cable along the arm and the possible additional EVA required for connecting the cable between orbiter and cherry picker.

Preliminary evaluation indicates that the existing Shuttle RMS power transfer capability of 250 W is adequate, i.e., 180 W illumination/ stabilizer (series usage) + 40 W controls and displays.

1.7 COMMUNICATIONS AND DATA

1.7.1 EMU versus OCP Hardwire

Communication links exist between the EVA astroworker and the Orbiter via the EMU. This is the recommended approach for OCP operations as it negates the need for establishing new interfaces between the EMU and RMS, RMS and Orbiter communications subsystem. However, backup means of communiaation should be provided and could involve the implementation of a hardwire link.

1.7.2 OCP Computer or Orbiter Computer

Figure 21 shows the Shuttle RMS data transfer, and Figure 22 shows the simplified system block diagram. The figures show that all communications between controls and displays (C&D) and general purpose computer (GPC), C&D and arm based electronics (ABE), and GPC and ABE are handled through the manipulator control interface unit (MCIU). The only exception to the above rule is that there is hardwired connection between C&D and ABE in direct drive (backup) mode of control. The OCP mode of the control essentially involves duplicating the C&D subsystem in the OCP. The question of whether to use a computer in OCP or the orbiter computer can be decided on the basis of the following factors:

- The orbiter computer can support all OCP control functions except possibly the collision/obstacle avoidance functions in its present configuration
- Using the orbiter computer requires minimum change in the system architecture. All that is required is the provision of MCIU to C&D data bus to the OCP and a OCP C&D to MCIU data bus with suitable multiplexing and demultiplexing at the OCP C&D and at the MCIU
- Parallel operation of port and starboard arms can be accomplished by using the Shuttle RMS hand controllers and OCP hand controllers simultaneously provided (1) the MCIU functions are duplicated by providing a second MCIU; (2) all principal function routines in the orbiter GPC which perform the required mathematical and logical operations to support the Shuttle RMS are made re-entrant with suitable modifications
- If an OCP computer is used:
  - The OCP computer must be a general purpose computer, with large memory and possibly mass storage and provisions for peripherals such as DEU's
  - The OCP computer must be designed to survive the cargo bay environment in a powered-down configuration, with provision for handling brown-out, or power-off interrupts
  - The capacity of the OCP computer will be comparable to that of a minicomputer with 32 k core, 1 μs memory cycle time and a hardware floating point unit

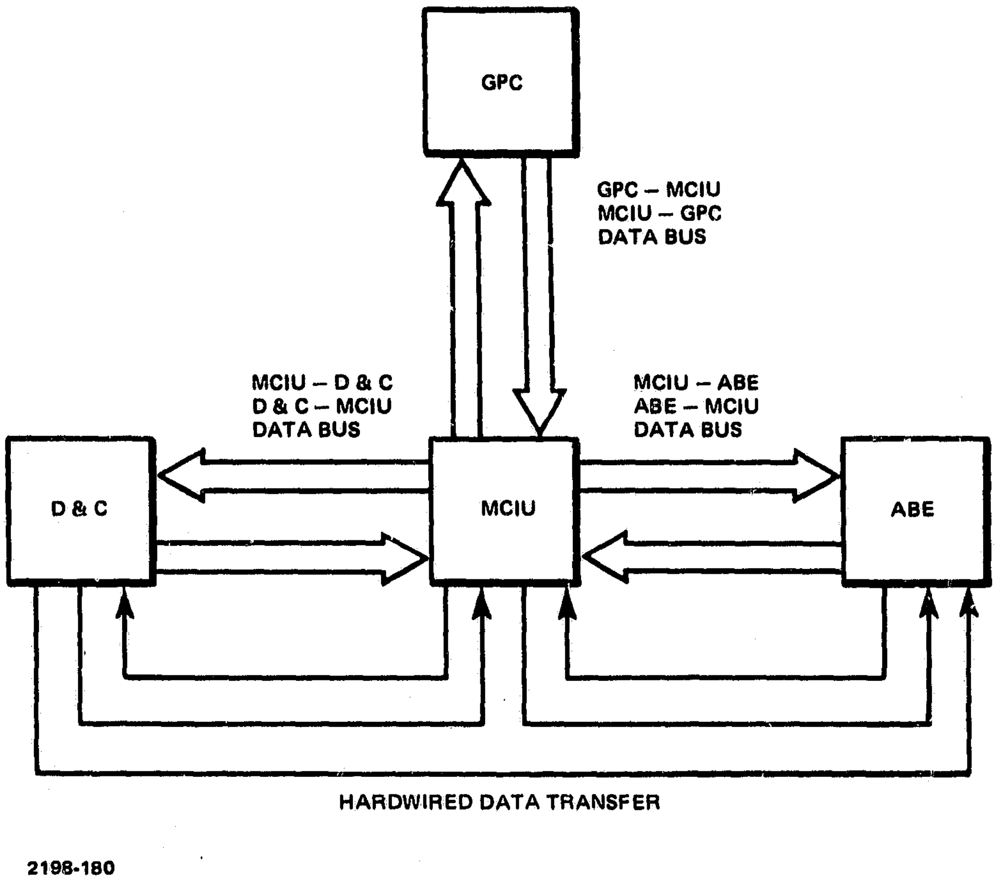

Figure 21. Shuttle RMS Data Transfer

GPC = GENERAL PURPOSE COMPUTER
MIA = MULTIPLEXER INTERFACE ADAPTOR
MCIU = MANIPULATOR CONTROLLER INTERFACE UNIT
ABE = ARM BASED ELECTRONICS
KYBD = ORBITER KEYBOARD ENTRY

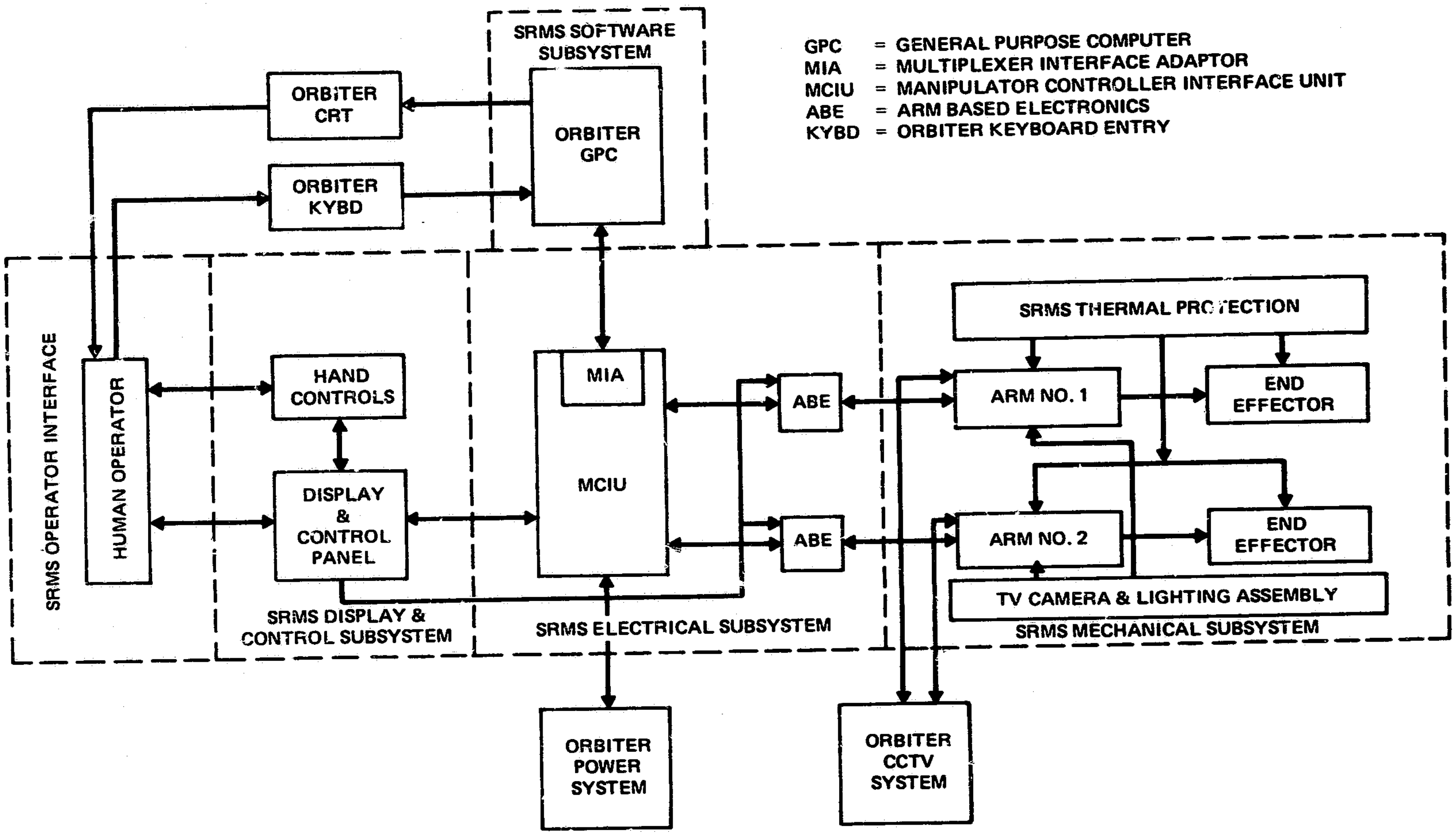

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Figure 22. Simplified System Block Diagram

- Because of the presence of two computers in the system (orbiter GPC and OCP computer) performing similar functions, the system must be capable of handling protocol and priority related problems
- Additional power and weight penalties
- With the present Shuttle RMS configuration, the OCP computer can perform control related functions only through the MCIU and as a result OCP computer-MCIU, MCIU-OCP computer data bus will be required

- A non-general purpose computer in the OCP may be used to perform multiplexing, demultiplexing, and data formating functions
- Spare capacity of the orbiter computer may increase due to:
  - Upgrading of the computer in future
  - Reduction in developmental software during operational flights.

In view of the above, it is recommended that the orbiter computer be used for OCP control. Further studies are recommended to determine the available orbiter computer spare capacity that can be used during OCP development flights and the computer requirements for OCP control functions (collision/obstacle avoidance in particular).

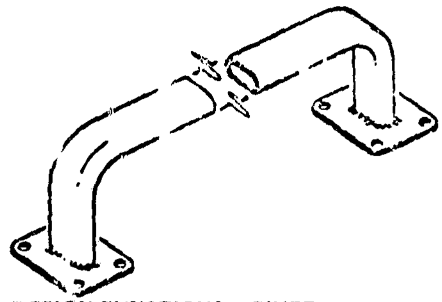
1.8 CREW ACCOMMODATIONS

1.8.1 Restraint System

1.8.1.1 Restraint System Issue - In a zero gravity environment, proper restraint of the extravehicular crewman at his worksite is mandatory to ensure a successful EVA mission. In this application, the astronaut is perched on an open platform from where he must gain access to the worksite. To accomplish his goal of spacecraft construction, repair, buildup, service, and retrieval, a well designed support and restraint system is essential. It must secure him firmly to the platform so that he can use both hands for accomplishing his work. It must permit him to bend, reach and exert forces, and he must have some lateral movement on the cherry picker platform.

1.8.1.2 Design Approaches - Extensive studies have been performed in the area of support and restraint. Figures 23 through 27 illustrate systems that have been used on past space flights and those contemplated for EVA operation on the Shuttle. These devices can be considered for use on the open cherry picker.

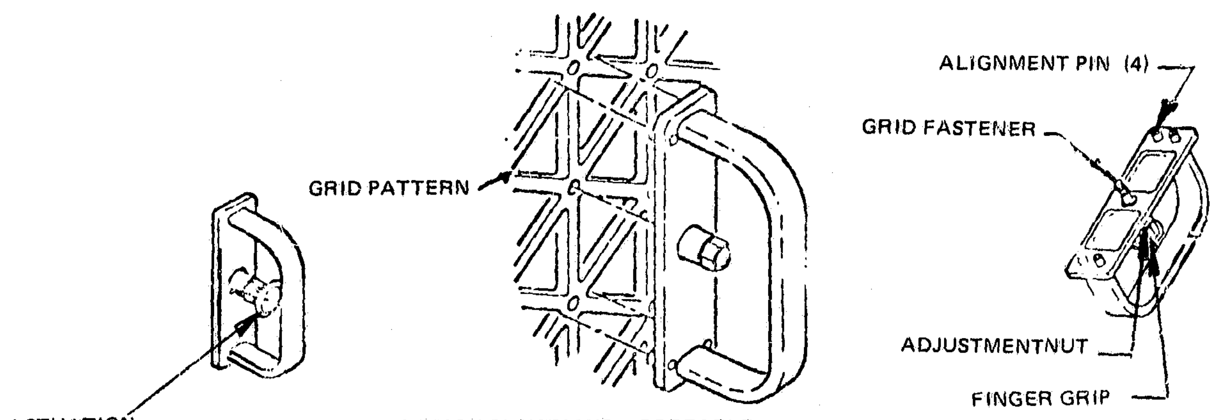
FIXED HANDHOLD



DESIGN FUNCTIONS – FIXED

- ONE-HAND SUPPORT WHILE WORKING WITH OTHER HAND
- PROVIDE PUSHOFF POINT WHEN TRANSLATING TO ANOTHER POSITION
- PERCH WHEN REACHING TO A DISTANT POINT

PORTABLE HANDHOLD



DESIGN FUNCTIONS – PORTABLE

- PLACE HANDHOLD IN OPTIMUM POSITION AT GIVEN WORKSITES
- ALTER HANDGRIPS LOCATION AS WORKSITE MOVES
- RE-ORIENT HANDGRIP IF WORK ANGLES CHANGE
- USED IN PAIRS FOR TRANSLATION
- USED AS A TETHER FOR LOOSE GEAR

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Figure 23. Handholds Support

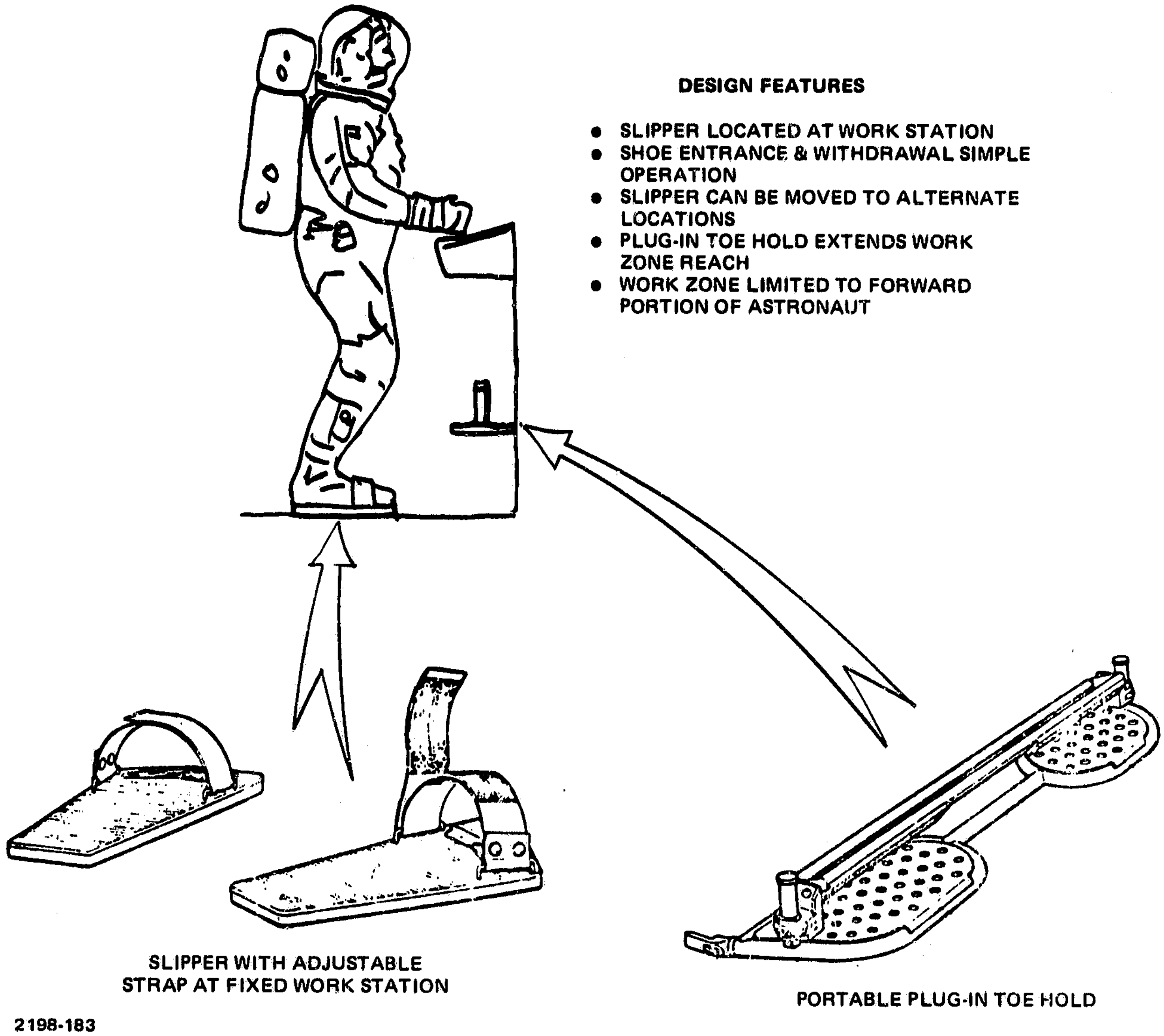
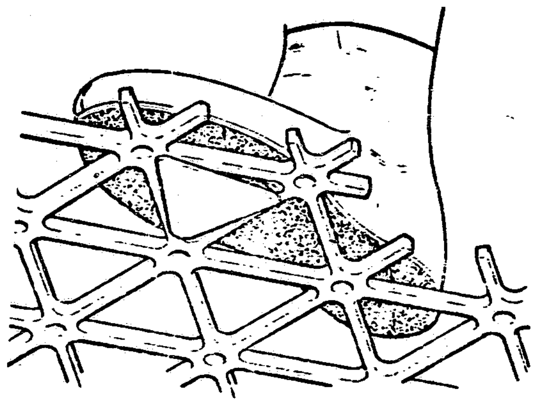
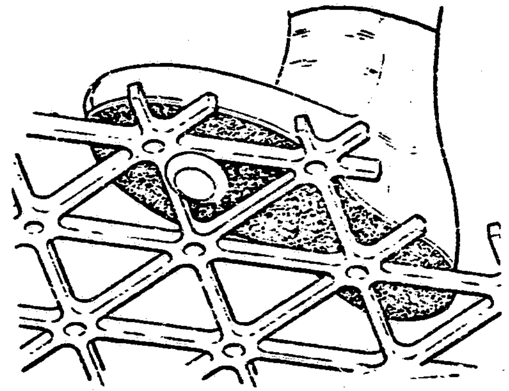


Figure 24. Toehold Restraints



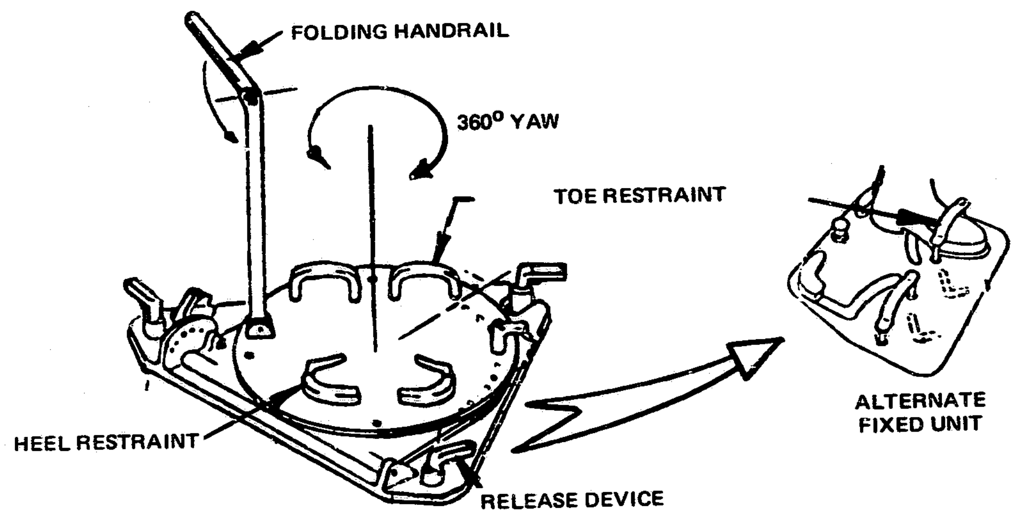
BOOT WITH TRIANGULAR
CLEAT ATTACHMENT



BOOT WITH CIRCULAR/
CONICAL CLEAT ATTACHMENT

DESIGN FEATURES

- COMPATABLE WITH EMU BOOT DESIGN
- GRID PATTERN IN FLOOR PROVIDES MULTIPLE LOCATIONS
- OPERATOR WORK ZONE 360° & UNLIMITED IN TRANSLATION
- TIME CONSUMING IN ENGAGING CLEAT INTO FLOOR GRID



ROTATING/MOVEABLE FOOT RESTRAINT

DESIGN FEATURES

- SECURES BOOT RIGIDLY
- BOOT EASILY ENGAGED
- 360° WORK ZONE
- WORK ZONE CAN BE EXTENDED BY MOVING ASSEMBLY TO NEW LOCATION

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Figure 25. Foot Restraint

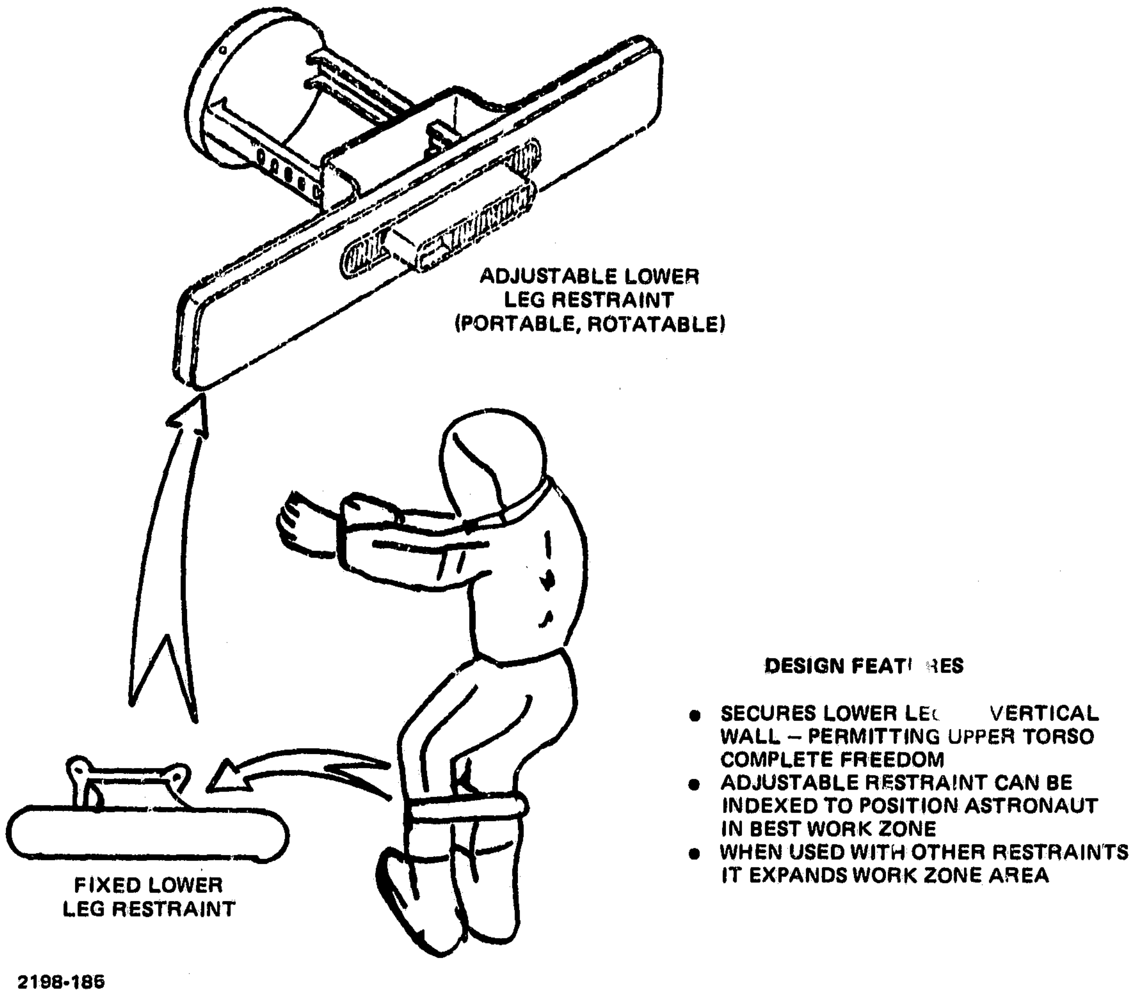
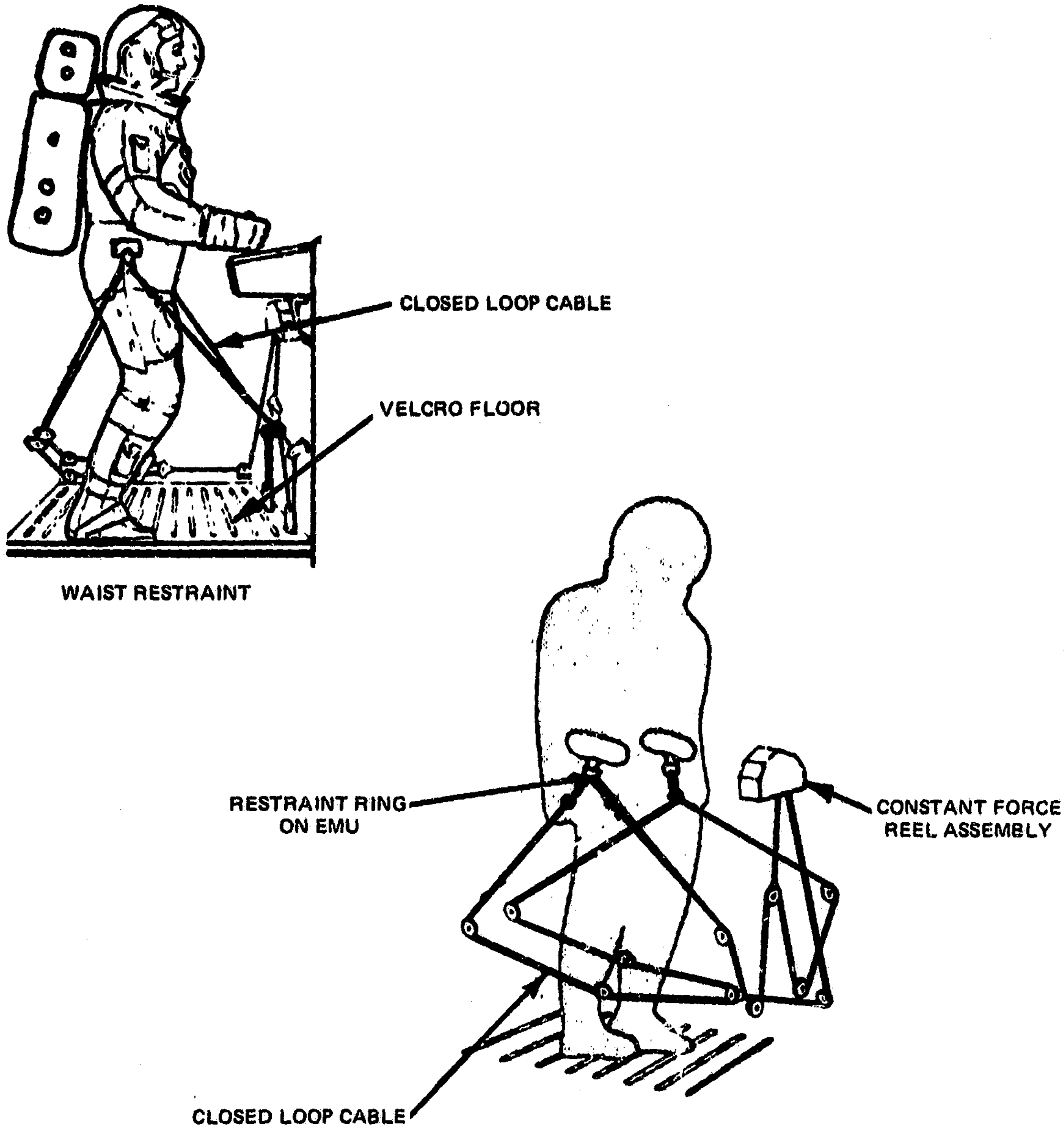


Figure 26. Lower Leg Restraint



DESIGN FEATURES

- APPLIES CONSTANT FORCE DOWNWARD AT HIP
- PERMITS LIMITED MOVEMENT AT WORK STATION
- WHEN USED WITH VELCRO FLOOR PERMITS UNLIMITED FOOT MOVEMENT
- LIMITS WORK ZONE TO SIDE & FORWARD QUADRANT
- FITS ALL PERCENTILE CREW MEMBERS

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Figure 27. Waist Restraint

1.8.1.3 Selected Support and Restraint System - For the open cherry picker, the restraint system must secure the operator firmly to his station when controlling the RMS movement. It must also hold him and permit him to use both hands freely when performing his work tasks.

A foot restraint will hold the operator's feet firmly to the floor and allow complete freedom of his upper torso. The two systems available are shown in Figure 25. The boot with the cleat added was used in the Skylab program. Comments on this system were that it met its design goals, but was time consuming engaging the cleat with the grid floor when moving about. If not careful the cleated engagement could be undone and the crewman would be airborne. All the forces applied by the creman's arms will have to be taken out at the balls of his feet. Over a long duration, this single reaction point will produce undue stress on his ankles and calves.

The other restraint system shown on Figure 25 secures the entire boot. It is easily engaged and will not disengage unintentionally as easily as the cleat device. Reaction loads are taken out over a longer couple, thus reducing wear on the ankles and calves. By placing this device on a rotating plane, a full 360° range of action can be achieved. The one disadvantage of this unit is that the lateral movement is limited.

The foot restrain should be supplemented with handholds.

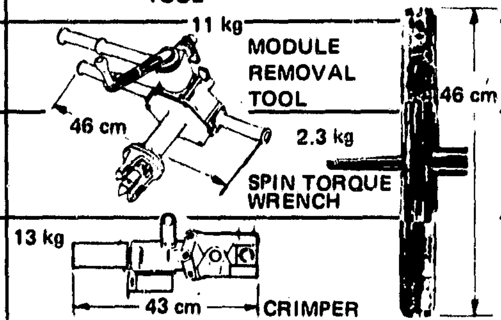
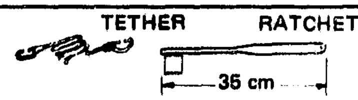
1.8.1.4 Required Simulation Analysis - The baseline support and restraint system should be tested in a zero gravity environment. This can be achieved in a partial mockup in the KC-135 or neutral buoyancy tank. The tests should determine the adequacy of the selected system, and also evaluate the other systems shown in Figures 23 through 27.

1.8.2 Tool Requirements

1.8.2.1 Discussion - The EVA astroworker should have ready access to the tools needed for task accomplishment. Selected tools required for open cabin platform cherry picker operations analyzed in Appendix A are illustrated in Table 11. The MMS module replacement tool at 0.46 m long and protruding 0.33 m seems to be the most awkward for storage. Most assemblies required bolts or screws for attachment, therefore a tool like the spin torque wrench shown should be included in the tool kit. A crimper or equivalent will be needed to join beams together. The conceptual

TABLE 11

NEAR-TERM OPEN CHERRY PICKER TOOLS

MISSION	FUNCTION	TOOL
MULTIMISSION MODULAR SPACECRAFT	TIGHTEN/LOOSEN MODULE RETENTION BOLTS	
LONG DURATION EXPOSURE FACILITY	TIGHTEN/LOOSEN RETAINING BOLTS	
LARGE SPACE STRUCTURE	CRIMP BEAM JOINTS	
SPACE CONSTRUCTION AUTOMATED FABRICATION EXPERIMENT	WELD BEAMS	
INITIAL CONSTRUCTION BASE	TIGHTEN BOLTED ASSEMBLIES	

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configuration of the tool illustrated is easy to stow and is needed for this specific task. Simple torque wrenches and means to tether them should be provided as standard items for tool kits.

1.8.2.2 Recommendation - The compliment of tools should be customized to the tasks to be performed. This implies that if an MMS module is to be removed, there is no requirement to have a crimping tool available. However, certain items are required during all assembly operations such as tethers. Therefore, it is recommended that the tool box be large enough to accommodate a mission custom item such as the MMS module bolt removal tool, a powered screw driver (LDEF) and other smaller items: tether, torque wrench, etc. A box 50-cm long, 35-cm wide, and 20-cm deep capable of supporting 20-kg mass should accommodate the aforementioned items plus room for other assembly items (pins, clips). The tools are retained by lanyards/tethers, magnetism, and clips.

1.8.3 Rescue Provisions (Open Cherry Picker)

Contingencies requiring crew rescue are:

- Crew incapacitated
- Cherry picker crane arm control malfunction.

In the event of the crew requiring immediate assistance, another astronaut should be available for rescue tasks. The second astronaut could traverse by utilizing an MMU or a second cherry picker. If the cherry picker arm is immobile, then the astroworker could use it in a hand over hand manner to return to the habitation center.

It is concluded that traverse provisions should be added to the Shuttle RMS.

1.8.4 Lighting

Illumination is required for dark side passes and, in some instances, is needed during sunlight operations to modify harsh shadows. Over-the-shoulder lighting has historically been the best approach and is recommended for space construction activities. Two flood lights located above the astroworker's head, one on each side, approximately 1-m distance from the head, with a beam width of 45 - 60° and adjustable pointing providing 50-ft candles at the worksite would permit night operations as illustrated in Figure 28. A third light is desirable, mounted at the astroworker's knees, also adjustable to illuminate the underside of the assembly area.

Cherry picker controls and displays should be provided with integral lighting. A portable light must also be provided to illuminate the tool/material storage bin.

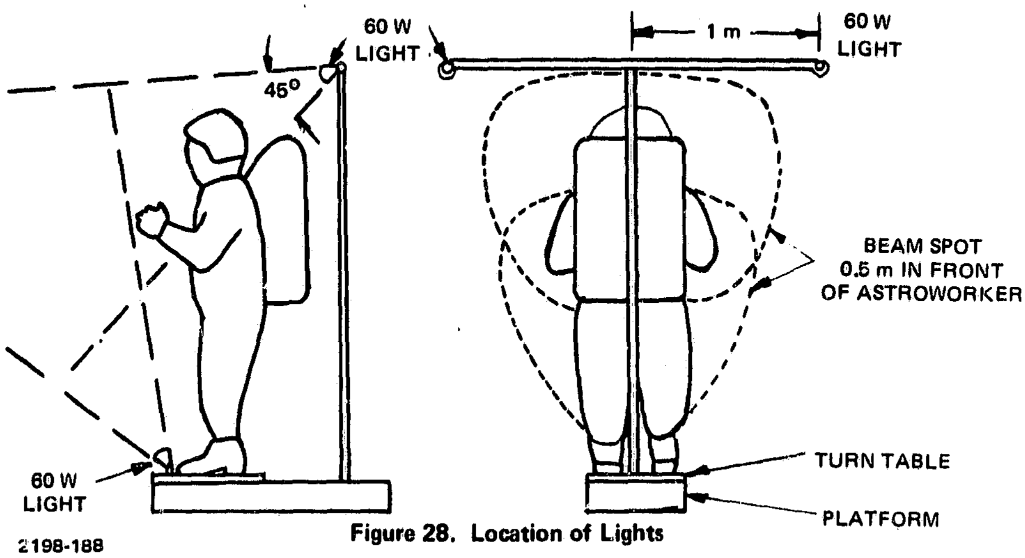

Figure 28. Location of Lights

Section 2

CLOSED CABIN CHERRY PICKER

2.1 INTERFACES

2.1.1 Cherry Picker Crane Mechanical Interface

The interface of the cherry picker to the space crane will depend on whether the cherry picker is to be a permanent fixture or whether it is only intended for use in specific cases.

- Permanent Interface - This will be the simplest to implement and can be configured to suit the cherry picker design as it evolves
- Temporary Interface - This will require a grapple fixture on the cherry picker and an end effector similar to that employed on the Shuttle RMS/OCP concept. Careful consideration will have to be given to the torque and force transfer requirements across the interface. It is recommended a safety line is strung between the cherry picker and arm to counter a possible end effector/grapple failure.

2.1.2 Power and Signal Line Routing to Cherry Picker via Crane Arm

The power and signal routing to the cherry picker via the crane arm will be similar to that used on the Shuttle RMS with a cherry picker. The maximum power may be higher and the number of signal lines increased, but the principles will be similar, i.e., provision should be made for the two data bus cables, power lines, several twisted pairs and single conductors. The number of cores incorporated will be mainly determined by the total number physically possible so that extras may be included at the initial stage.

The inclusion of two TV monitors at the cherry picker arm will require two co-axial cables, although it is possible to carry the information to both down the same cable using different carrier frequencies. Voice communication can be included on these cables.

2.1.3 Controls and Displays Requirements to Operate Crane from Cherry Picker

The controls and displays requirement to operate the space crane from the cherry picker will be similar to the controls and displays to operate the Shuttle RMS from the cherry picker. However, because the operator will not be in his EVA suit, he will have much more dexterity and mobility and, therefore, he will be able to carry out more tasks if required.

It is considered that the main tasks he will be required to perform when in the cherry picker will be to position the cherry picker arm and then control the manipulators on the arm or to position the cherry picker arm and control the other arm. He will not be required to operate both arms simultaneously and, therefore, one single control station should be satisfactory. Consideration should be taken of using the TV monitor (which is required for controlling the other arm) and superimposing the control data.

The hand controllers could be the same type as in the Shuttle.

A major consideration of the controls and displays is the philosophy of operation of the crane and whether one operator will always be in the crane cabin. If it is decided that he will, then the cherry picker may be considered to be just an arm movement control input and monitoring station and all the backup systems can be contained within the crane cabin. However, if the cherry picker operator may be the only operator in the system, then all the backup systems, i.e., single-joint drive, direct, and backup, must be available at the cherry picker station.

2.1.4 Cherry Picker Crane Stiffness and Strength Requirements

The requirement to be able to exert 220 N (50 lbf) at the tip of the crane will be a major factor in determining the strength of the arms and joints.

End point accuracy will be a key requirement in determining the stiffness of the arms and drive trains. In addition, the allowable deflection of the end point when the maximum tip force is exerted must be kept within reasonable limits. It is considered this deflection should be less than 6 in. so that the cherry picker operator will remain in a reasonably stable position with respect to the structure on which he is working.

Detailed analysis will be required to determine the contribution of each crane element to the stiffness and strength of the overall assembly such that an optimized design can be produced.

2.1.5 Crane Obstacle Avoidance Techniques

Methods of obstacle avoidance and the procedures used to develop these will be similar to OCP/Shuttle RMS obstacle avoidance approach discussed in Paragraph 1.1.5, and consequently no further discussion is required. Apart from the size, there are two important differences between the space crane and the Shuttle RMS, viz., the ability of the space crane to bend the elbow both ways, and the upper arm roll joint present in the crane. The presence of the seventh joint and the ability to bend the elbow both ways enables the crane to have an infinite number of configurations (and consequently elbow positions) for a required end effector orientation and position.

Resolved rate control of the crane will be carried out using a pseudo-increase approach to solve for the joint rates. The possibility of infinite number of configurations increases the complexity of the obstacle avoidance algorithm but provides greater potential for avoiding obstacles. Potential collisions between the crane and the structural elements in the vicinity can be avoided by changing the location of the elbow and hence the configuration. In addition to the resolved rate control, an algorithm can be developed for moving the elbow while holding the position and orientation of the end effector fixed. Such an approach will permit effective obstacle avoidance in manual operation as well as manual operation with computer caution and warning.

2.1.6 Visual Aids (CCTV) Required for Obstacle Avoidance

The visual aids required for obstacle avoidance in the case of the space crane depends primarily on the details of the work area of the crane, the method used for obstacle avoidance, and whether the operator is in a supervisory mode or an active participant in obstacle avoidance. The objectives of the provision for visual aids are:

- Provide caution and warning against impending collisions
- Provide complete visual access to the crane operator (whether in the crane cabin or in the cherry picker) of all parts of the crane, cherry picker and the crane cabin and turret
- Provide visual access to all structural elements present within the reach envelope of the crane.

In automatic modes of crane operation, the crane will be controlled by the GPC software and the operator will monitor the operation. If possible collisions are recognized by the operator from direct views and/or CCTV views, he will intervene to perform obstacle avoidance.

In manual mode of crane operation, the crane will be controlled by the operator through the hand controllers, using direct views and/or CCTV views. Caution and warning against possible collisions will be provided by collision avoidance software.

To meet the objectives listed above, the following visual aids will be provided:

- A caution annunciator with an audio alarm to indicate to the operator that if he continues to move the crane on its present course, a collision is likely and consequently he should slow down and perform obstacle avoidance
- A warning annunciator with an audio alarm to indicate to the operator that a collision is impending and consequently brakes have been applied to stop the crane
- A pair of CCTV cameras on the crane with a pair of monitors in the C&D system to provide visual access to all parts of the crane and surroundings. The requirements for the CCTV system are specified in Paragraph 3.1.5
- Additional TV cameras mounted on the cherry picker and the crane turret and cabin
- Cameras on surrounding structural elements to provide complete visual access to all regions of the crane reach envelope and its vicinity
- The caution and warning software will also provide information on the location of impending collisions and designate the optimum camera view with the required pan and tilt angles for the operator's use
- In a resolved rate controlled system, the direction of motion of the crane required to avoid impending collision with an obstacle can be presented to the operator in the form of differential (required-actual) velocity components either on the CCTV monitor or in a head-up display. By nulling the differential using the hand controllers, the operator will be able to avoid obstacles.

2.2 STRUCTURE

2.2.1 Closed Cherry Picker Size and Geometry

The size and geometry of the closed cherry picker is a function of many elements. The results of trade studies on these elements will have an impact on the final configuration of the cherry picker cabin. For an overall cabin design evaluation, information from trades and evaluation discussed in other sections of this report are used. The recommended design requirements will then be used to establish a baseline closed cabin cherry picker. The key cabin design elements are listed below:

- Crew Size and Number of Control Stations
- Docking/Berthing - Size, Location, Quantity
- Growth Capability of Baseline
- Vision Requirements - Direct and Indirect
- Airlock Requirements
- Rotary Bearing - Size
- Dexterous Manipulator - Geometry, Size, Range of Motion
- Stabilizer - Geometry, Size
- Manipulator Controller - Geometry, Size, Motion, Indexing
- Stabilizer Controls - Geometry, Size, Motion
- Controls and Displays
- Support and Restraint
- Subsystem Definition and Location
- Radiator Requirements
- Crew Accommodations.

2.2.1.1 Crew Size and Number of Control Stations - Alternate arrangements for the MRWS cabin design are presented in Figure 29. These alternates embody the following features:

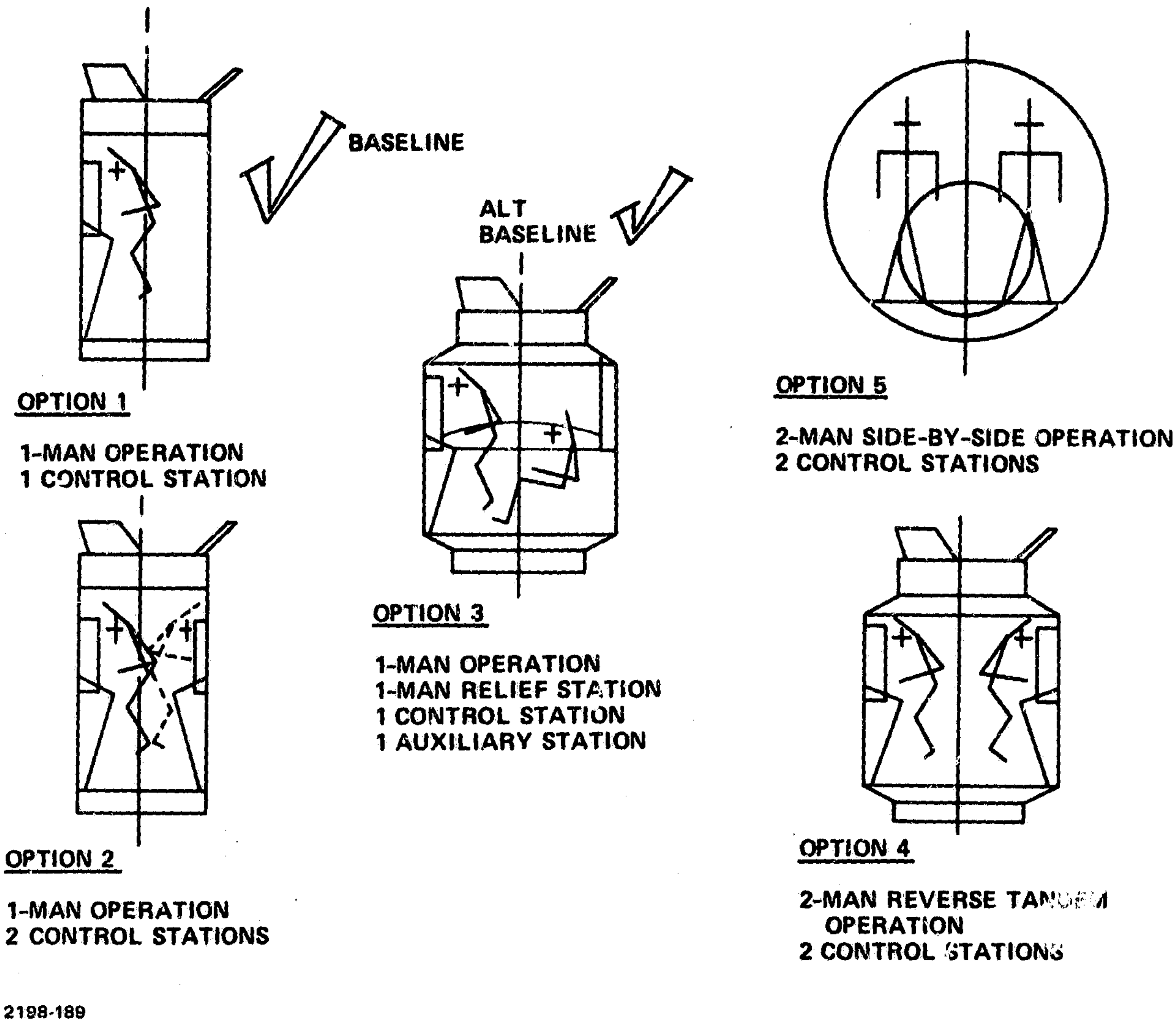

Figure 29. Trade Study – Cabin Concepts

- Option 1 - A one-man cabin with a diameter of approximately 1.8 m is operated from a single console. A rotatory bearing, located at the bottom of the cabin, provides 360° rotation relative to the crane arm/cherry picker interfaces. This feature provides nearly 2 Pi steradian vision with a single forward positioned window.

- Option 2 - A one-man cabin with a diameter of approximately 1.8 m is operated from two crew stations. One crew station is used for dexterous manipulator work and the second is used to operate the grappler and crane arm. A 360° rotary bearing provides the capability of placing either crew station in a forward looking position.

- Option 3 - A two-man cabin with a diameter of approximately 2.1 m is operated by one man from a single station. It has sufficient room for a relief man. A 360° rotary bearing provides nearly 2 Pi steradian vision.

- Option 4 - A two-man cabin with two operator stations splits crew responsibility between the dexterous manipulator operator and the grappler/crane arm operator. A 360° rotary bearing is provided to interchange the viewing conditions of each operator.

- Option 5 - A two-man cabin with two operator stations splits crew responsibilities utilizing a side-by-side arrangement.

The operational impact of having two operators in a MRWS is illustrated in Table 12. Assuming that the master controls selected permit one operator to handle two dexterous manipulators, it appears that in most cases, the second operator availability would not allow improvement in the time to perform tasks. The first task listed in the table, install module/component, provides no improvement during positioning, aligning, and holding because these are serial operations. Installation of fasteners is one task that two manipulators could work on in parallel, each operator controlling a manipulator and installing fasteners somewhat independently of the other, once the module is in its aligned position. Assuming 16 fasteners to be installed at 1 min each and that two fasteners are required to hold the module in position, this allows each operator to install seven more in parallel, providing a saving of 7 min.

TABLE 12

OPERATIONAL IMPACT OF TWO OPERATORS

FUNCTION	OPERATIONAL PROCEDURE	TASK TIME (MIN)	TASK TIME EFFECT OF TWO OPERATORS
INSTALL MODULE/COMPONENT	• GRASP MODULE	2	• NO IMPROVEMENT DURING POSITIONING, ALIGNMENT & HOLDING
	• MOVE TO INSTALLATION LOCATION	2	• IF MANY FASTENERS ARE INSTALLED, EACH OPERATOR COULD OPERATE A MANIPULATOR & REDUCE TIME (7 min) TO INSTALL FASTENERS
	• COMMENCE ALIGNMENT	1	• TOTAL TIME 17 min
	• APPLY CORRECTION (ITERATE)	2	
	• HOLD IN FINAL POSITION	–	
	• INSTALL FASTENERS	16	
	• INSPECT INSTALLATION	1	
	TOTAL	24	
JOIN STRUCTURE	• GRASP BEAM	2	• A SECOND OPERATOR OFFERS NO IMPROVEMENT IN OPERATIONAL TIME
	• MOVE BEAM TO ATTACHMENT LOCATION	5	• TOTAL TIME 15 min
	• COMMENCE ALIGNMENT	2	
	• APPLY CORRECTION (ITERATE)	3	
	• INSERT INTO JOINT FITTING	–	
	• FASTEN JOINT	2	
	• INSPECT	1	
	TOTAL	15	
INSTALL ELECTRICAL CABLE	• LAY CABLE ALONG BEAM	2	• CABLE ATTACHED AT 7.5-m INTERVALS DOES NOT PERMIT PARALLEL ATTACHMENT DUE TO LIMITATION IN MANIPULATOR REACH, THEREFORE UNABLE TO UTILIZE SECOND OPERATOR
	• POSITION CABLE AT ATTACHMENT POINT	2	• TOTAL TIME 6 min
	• FASTEN CABLE	2	
	TOTAL	6	

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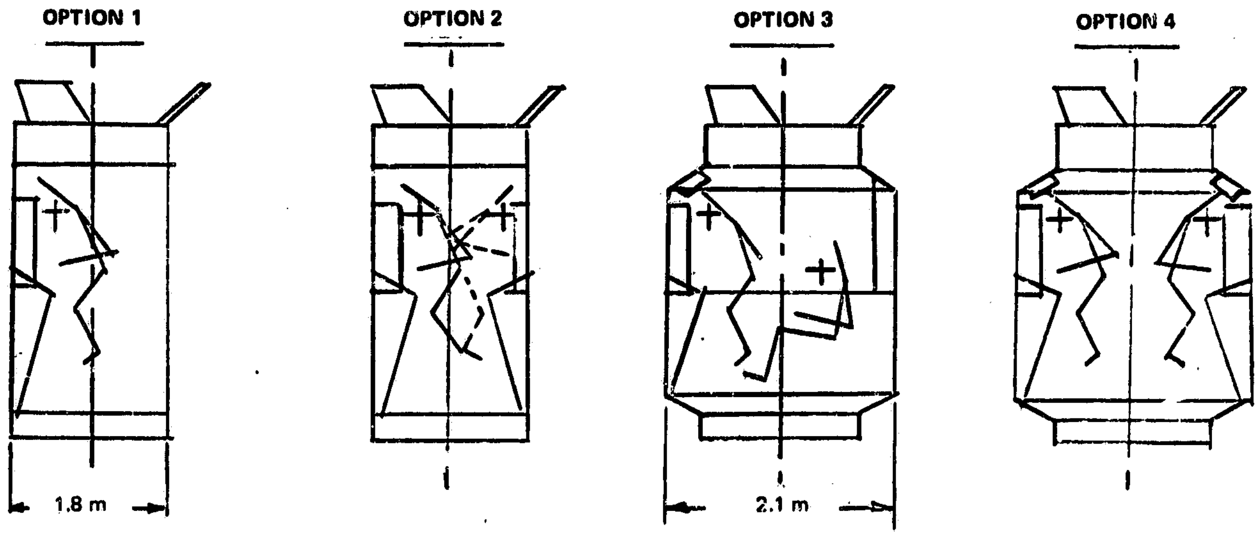
The second and third tasks illustrated are serial operations that would be done by one operator at a time. The operational advantage of a second operator for the tasks illustrated would be to minimize fatigue during repetitious activities, which may allow task time improvement during extended operations. A review of the tasks performed indicates that all operations can be performed by a single operator in a serial procedure. The time-line improvement for utilizing parallel operations needing the Option 5 side-by-side crew cabin is not sufficiently great to justify the added expense of the larger cabin.

2.2.1.2 Window Arrangement - Figure 30 illustrates the impact the window arrangements have on radiator sizing. Options 1 and 2 have the same radiator requirements as do Options 3 and 4. It is assumed that, because the windows are on opposite sides of the cylindrical cab, one side experiences heat loads from direct sunlight and the other has no heat loss, being in the dark side.

It can be seen that the required radiator area of Options 2 and 4 exceeds the available structural area for mounting radiator panels by a considerable amount. Options 1 and 3, on the other hand, provide sufficient mounting area for required radiator panels.

The selection of a cabin approach between Options 1 and 3 is primarily a cost consideration. Figure 31 presents an estimate of the impact cabin diameter has on Development (DDT&E) and first unit cost. The larger diameter Option 3 could be as great as $10M more to develop and $3M per unit to fabricate. If total costs, including operational costs, are compared, Option 3 shows an advantage (Table 13). These figures reflect the cost per shift for operating a single MRWS at a Solar Power Satellite construction base. The One-Plus-One Concept (Option 3) has the advantage that a backup man would increase relative vehicle utility. The cost of money for SPS construction has been estimated by Boeing to be as great as $2M per day. The improved productivity of Option 3 more than compensates for the added cost of transporting and housing a second man.

The relative total cost between Options 1 and 3 shown in Table 13 is sufficiently close under the assumptions made that the advantage Option 1 has in terms of near-term dollar expenditures is a more significant factor in selecting the smaller cabin design.



PARAMETER	OPTIONS 1	2	3	4
GLASS AREA (m^2)	0.63	1.26	1.0	2.0
REQUIRED* RADIATOR AREA (m^2)	7.2	7.2	8.4	8.4
AVAILABLE RADIATOR AREA (m^2)	7.2	6.2	9.6	7.0

*ASSUME – 650 W FOR SUBSYSTEMS, 400 W FOR METABOLIC LOAD

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Figure 30. Window Arrangement Design Impact on Radiator Requirements

$$\frac{\partial DDT\&E}{\partial DIA} = \$10.3\ m/ft$$

$$\frac{\partial TFU}{\partial DIA} = \$2.9\ m/ft$$

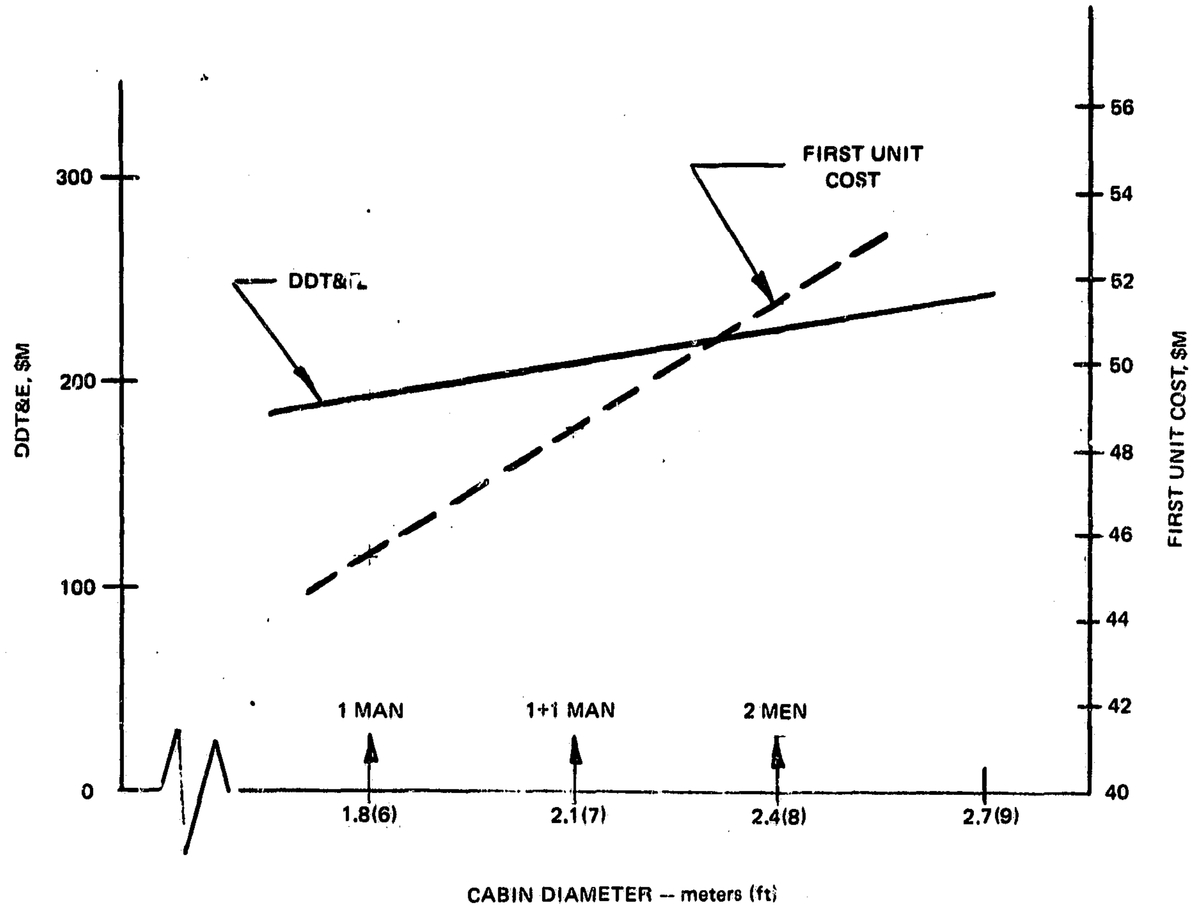

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Figure 31. Cost Sensitivity to Cabin Diameter

TABLE 13

EVALUATION OF LIFE CYCLE COST OF ONE VERSUS ONE + ONE MAN DESIGN DURING SPS CONSTRUCTION

EVALUATION DATA	COMPARISON: ONE	COMPARISON: ONE + ONE	BASIS AND/OR DATA RATIONALE
MRWS COST			
WEIGHT	3354 kg	3627 kg	PRELIM WEIGHT STATEMENTS
COST ELEMENTS			
RDT&E	$ 210 M	$ 230 M	KOLLE MANNED VEHICLE COST MODEL WITH 40% NEW TECH
UNIT	$ 21 M	$ 24 M	
TOTAL	$ 231 M	$ 254 M	
LAUNCH COST	$ 0.1 M	$ 0.1 M	30$/kg HLLV LAUNCH COST
AMORTIZED MRWS COST/ 8 hr SHIFT	(A) $ 2310	$ 2639	10-yr LIFE, 3 8-hr SHIFTS/day, RDT&E AMORT OVER 50 UNITS
CREW COST			
$ TO DEL MAN TO ORBIT	$ 0.285 M	$ 0.570 M	90-day STAY TIME, $20 m ÷ 70 MEM
COST TO HOUSE MAN	$ 1.47 M	$ 2.94 M	90-day STAY TIME, HABIT MODULE = $60 M/MAN/ 20 yr
AMORTIZED CREW COST/ SHIFT	(B) $ 6500	$13,000	(HABIT COST + DEL COST) ÷ (90 days) - (3 SHIFTS)
COST OF MONEY			
$/DAY	$ 2 M	$ 2 M	BOEING STUDY RESULTS
% CONSTRUCTION TIME INVOLVING MRWS	75%	75%	
COST OF MONEY/MRWS	$30,000	$30,000	0.75 X $2 m ÷ 50 MRWS
COST/SHIFT	(C) $10,000	$10,000	3 SHIFTS
MRWS COST/SHIFT	$18,810	$25,639	TOTAL (A), (B) & (C)
RELATIVE UTILITY FACTOR	0.65	1.0	ONE MAN REQUIRES REST
EQUIV COST/SHIFT	$28,938	$25,639	

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2.2.2 Docking/Berthing - Size, Location, Quantity

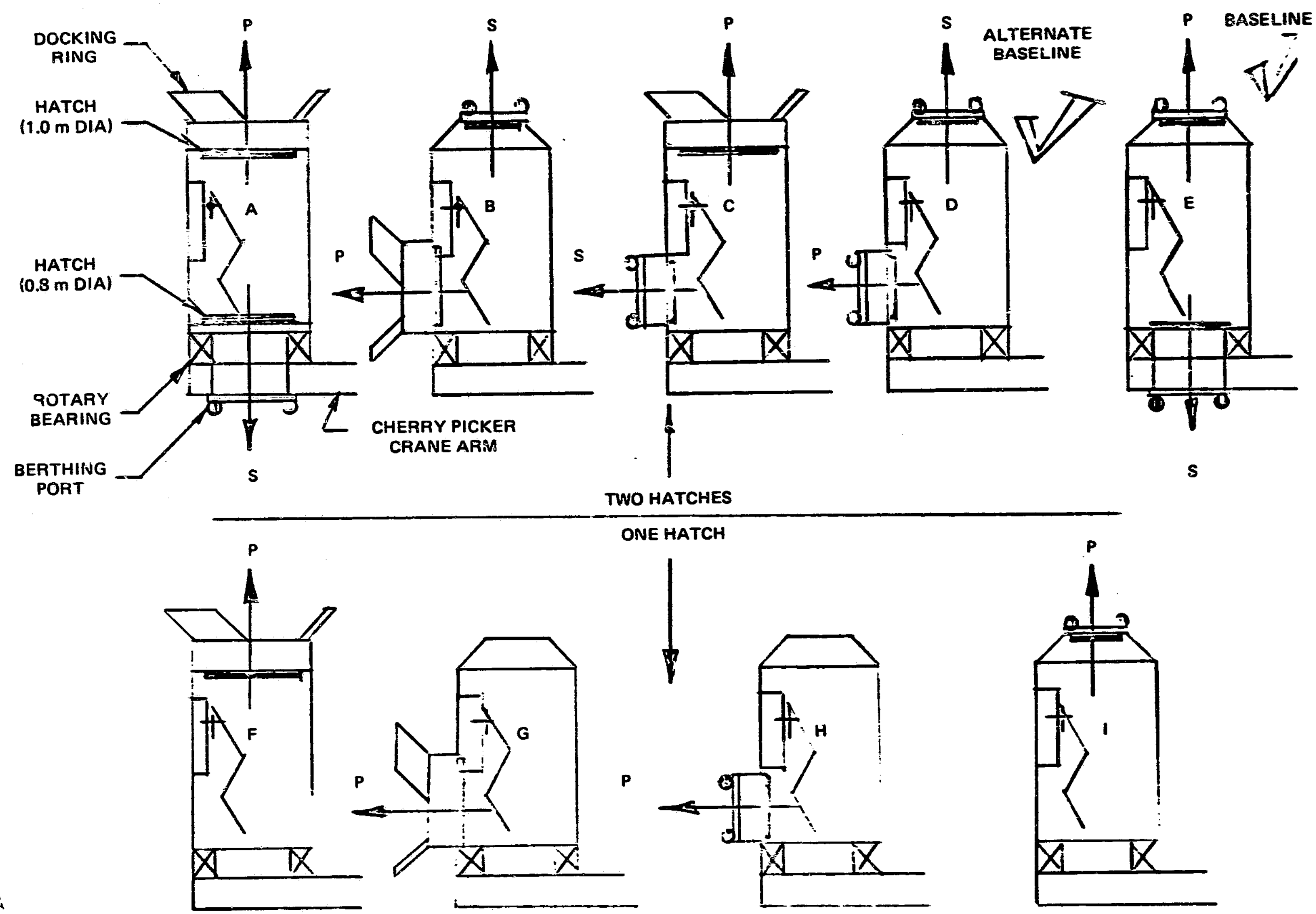
2.2.2.1 Docking versus Berthing - Two methods of mating space modules are being considered: docking and berthing. Docking is usually considered for the mating of two free flying spacecrafts, one being passive, the other active. The passive vehicle stabilizes itself while the active vehicle flies into it and engages the docking devices. Berthing is usually considered for the mating of two space modules which are connected by linkage. One vehicle has a crane arm which directs the other grappled vehicle to a simplified berthing port. The guided vehicle is pulled into the mating port and then latched (either automatically or manually).

The closed cherry picker falls into the berthing category. For this reason, Options A, B, C, F, and G (Figure 32) can be dropped from consideration. Candidate Options D, E, H, and I remain for consideration.

2.2.2.2 Quantity - The number of entrance/exit paths to a habitable volume must be considered next. One hatch in a small module such as the cherry picker seems to be a logical choice because of the limited internal volume. However, prudent human factors, design, and safety considerations dictate at least two ways in and out of any confined volume. For this reason, Options H and I can be dropped, leaving Options D and E (or a variation thereon) as the logical choices.

Configurations D and E have pro and con features:

- Configuration D
  - Pro
    - o Forward berthing provides direct vision to mating surfaces
    - o Forward berthing hatch swings into side console in open position
    - o Dexterous manipulator arms can be used to assist in berthing operations
  - Con
    - o Forward berthing port limits location and operation of dexterous manipulator arms
    - o Forward hatch restricts depth of forward console
- Configuration E
  - Pro
    - o Permits optimum location of dexterous manipulator arms



P = PRIMARY PATH
S = SECONDARY PATH

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Figure 32. Cherry Picker Trade - Docking/Berthing - Size, Location, Quantity

o Fits within internal diameter of rotary bearing

o Adaptable to growth into other MRWS configurations (see Figure 33)

- Con o Requires expensive rotary bearing sealing joints

o Crew restraint mounted on floor hatch

o Floor hatch awkward to open and close

o Berthing operation (secondary mode) difficult to see.

Based on these considerations, Configuration E will be used as the baseline vehicle. It should be noted that it will be more expensive than Configuration D. Note, berthing ports in the aft portion of the cabin were not evaluated because:

- Single control station baseline
- Equipment locations in the aft quadrant
- Radiator considerations.

2.2.3 Hatch Size

Design requirements state that a 1.0-m diameter opening be provided for hatches. This assumes a suited astronaut with backpack will pass through as will hardware and equipment. In the case of the cherry picker, a shirt sleeve operator will transfer into the small volume provided. The LM had a 32.0-in. diameter hatch, through which a fully suited astronaut with backpack crawled through in 1/6 gravity. For this reason and also to minimize swept volume, an 0.8-m diameter hatch should be considered as a viable option to the 1-m hatch.

If the growth concept of the cherry picker is considered, as shown in Figure 33, then a compromise will have to be made. For the sake of commonality and growth, the recommended 0.8-m diameter hatch will have to be abandoned in favor of the 1.0-m diameter hatch. For this study, the 1.0-m diameter hatch will be baselined for the upper hatch and a 0.8-m diameter for the lower hatch.

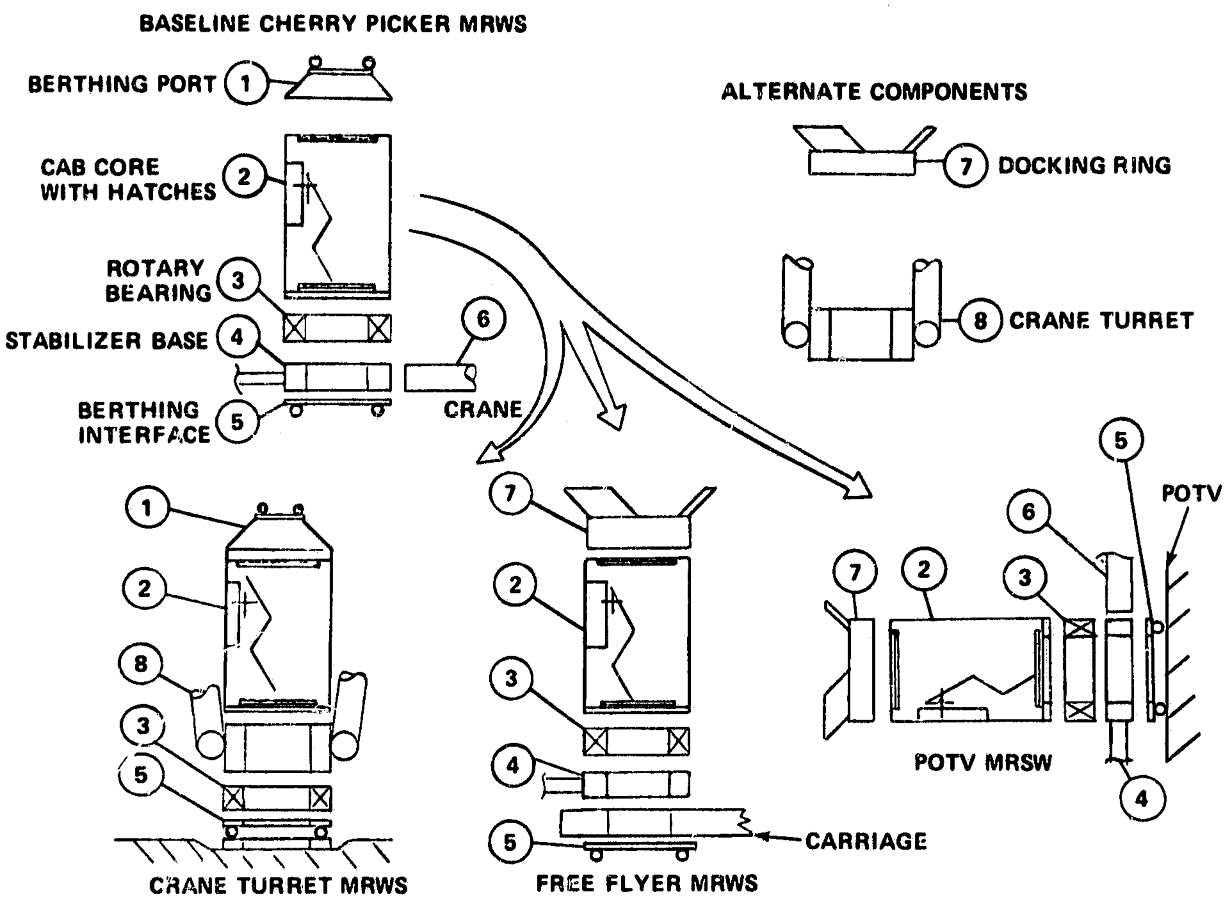

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Figure 33. MRWS Future Growth Trade

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2.2.4 Vision Requirements - Direct and Indirect

The basic design requirement for all MRWS vehicles is to provide as much visibility with minimum window area. The larger the glass area the greater are the problems with radiation protection, thermal losses, pressure shell continuity, and internal controls and displays. Large visibility view angles can be achieved with small window area by placing the design eye close to the glass, as in the LM. Indirect vision via closed-loop television can supplement the direct vision.

2.2.4.1 Closed Cabin Cherry Picker - The primary tasks of the operator in the closed cabin cherry picker are to assemble and repair space structures with dexterous manipulators. These arms will be functional 2 to 3.5 m from the operators design eye at a depression angle of 30° to 65° below a horizontal reference line. Primary work zone will be in front of the operator and this can be viewed with a 50° azimuth angle from design eye position. By expanding these view angles, as shown by secondary view area in Figure 34, the operator can see the grappler, dexterous manipulators, and surrounding structural elements being worked on. An overhead 30° conical view angle provides sufficient visual cues for berthing the cherry picker.

2.2.4.2 Turret Crane - The crane turret operator's primary task is to control the movement of two 35-m articulating crane arms. One crane arm transports hardware and assemblies while the other supports either an open or closed cabin cherry picker. The crane turret operator should have good visibility of both cranes through its entire range of motion. This requirement might place a severe design problem on window area. For this study, the angles depicted in Figure 34 will serve as a baseline visibility requirement. Further definition on the crane arm geometry and range of motion is needed to assess adequacy of windows. Because of the extreme distances involved, supplemental vision will have to be supplied by TV cameras mounted at the end of the crane.

2.2.4.3 Free Flyer - The free flyer visibility requirements are similar to the closed cabin cherry picker, except more extensive. In addition to providing downward vision for dexterous manipulator and grappler operation, it must provide forward visibility for the free-flight mode. Overhead vision will have to be provided for docking maneuvers and in addition downward vision for backup berthing maneuvers. The vision requirements are shown in Figure 34.

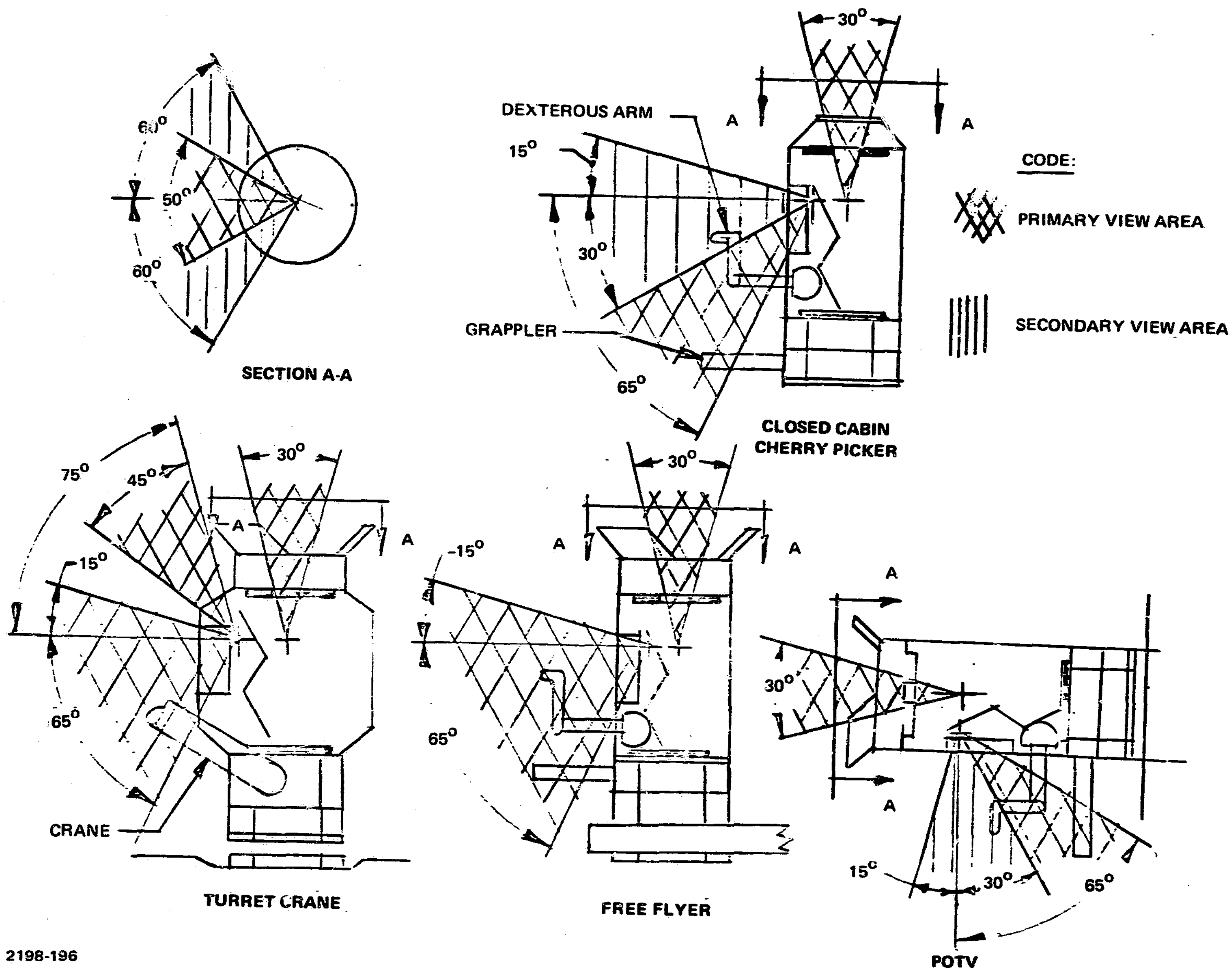

Figure 34. Visibility Requirements for MRWS Vehicles

2.2.4.4 POTV - The MRWS configuration for the Personnel Orbital Transfer Vehicle (POTV) at the present time is similar to the closed cabin cherry picker. The vision requirements are the same as shown in Figure 34.

2.2.4.5 Total Visibility Requirement - The combined vision requirements of the four MRWS vehicle are shown in Figure 35. For commonality of structure, as discussed in Paragraph 2.2.2.3, a window configuration providing this total vision is desirable.

2.2.5 Airlock Requirements

In all four MRWS configurations, the operators will be working in a shirtsleeve environment (14.7 psi two gas system, identical to base vehicles). Normal transfer from home base to MRWS is through a berthed or docked port. The operator enters the MRWS, checks out all subsystems, and closes the hatch. The MRWS separates from home base vehicle and starts its tour of duty. When its shift is complete, the MRWS returns to home base. During this entire normal operation, the operator is in a shirtsleeve mode and has no need for a space suit. In the event of an emergency, such as a pressure leak or immobile MRWS, a rescue mode is required. This situation has been analysed for the four different MRWS configurations.

2.2.5.1 Closed Cabin Cherry Picker Operating from Shuttle RMS - For the mission where the closed cabin cherry picker is utilized with the Shuttle on the end of the RMS, three rescue modes were considered. The upper part of Figure 36 shows the suggested normal transfer mode, and the lower part illustrates the rescue modes.

- Rescue Mode I - If the cherry picker is unable to return to the Shuttle airlock, the other RMS brings the airlock to the cherry picker and berths to it. The stranded operator enters the airlock and returns to the Shuttle cabin. The pros and cons of this approach are:

  - Pro
    - o No EMU has to be stored in the confined limits of the MRWS
    - o No pre-breathing (up to $3\frac{1}{2}$ hr) required in transferring to rescue vehicle
    - o MRWS is a true shirtsleeve environment as is the Shuttle
    - o Rescue time is minimal

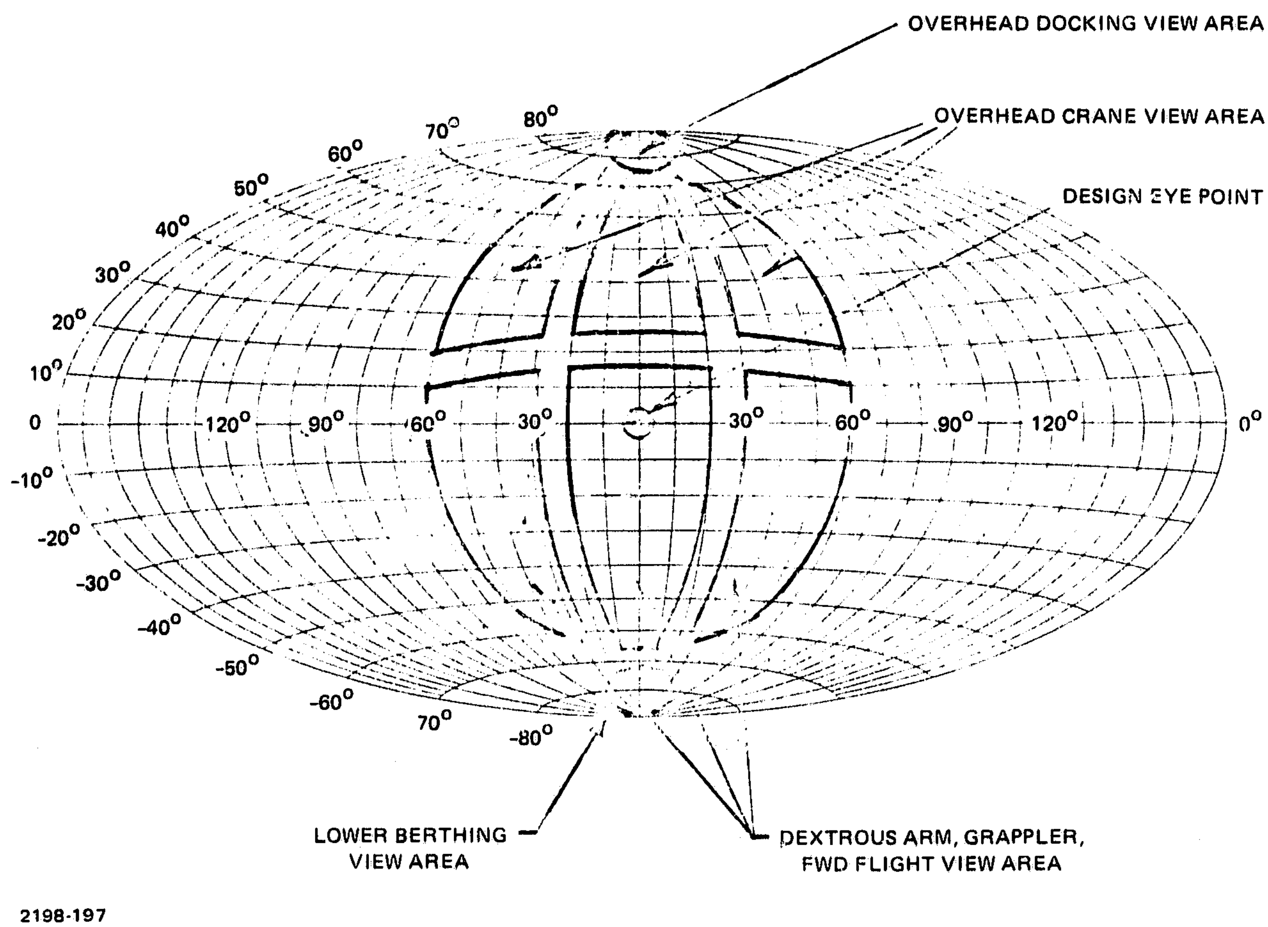

Figure 35. MRWS Visibility Requirements on AITOFF's Equal Area Projection of the Sphere

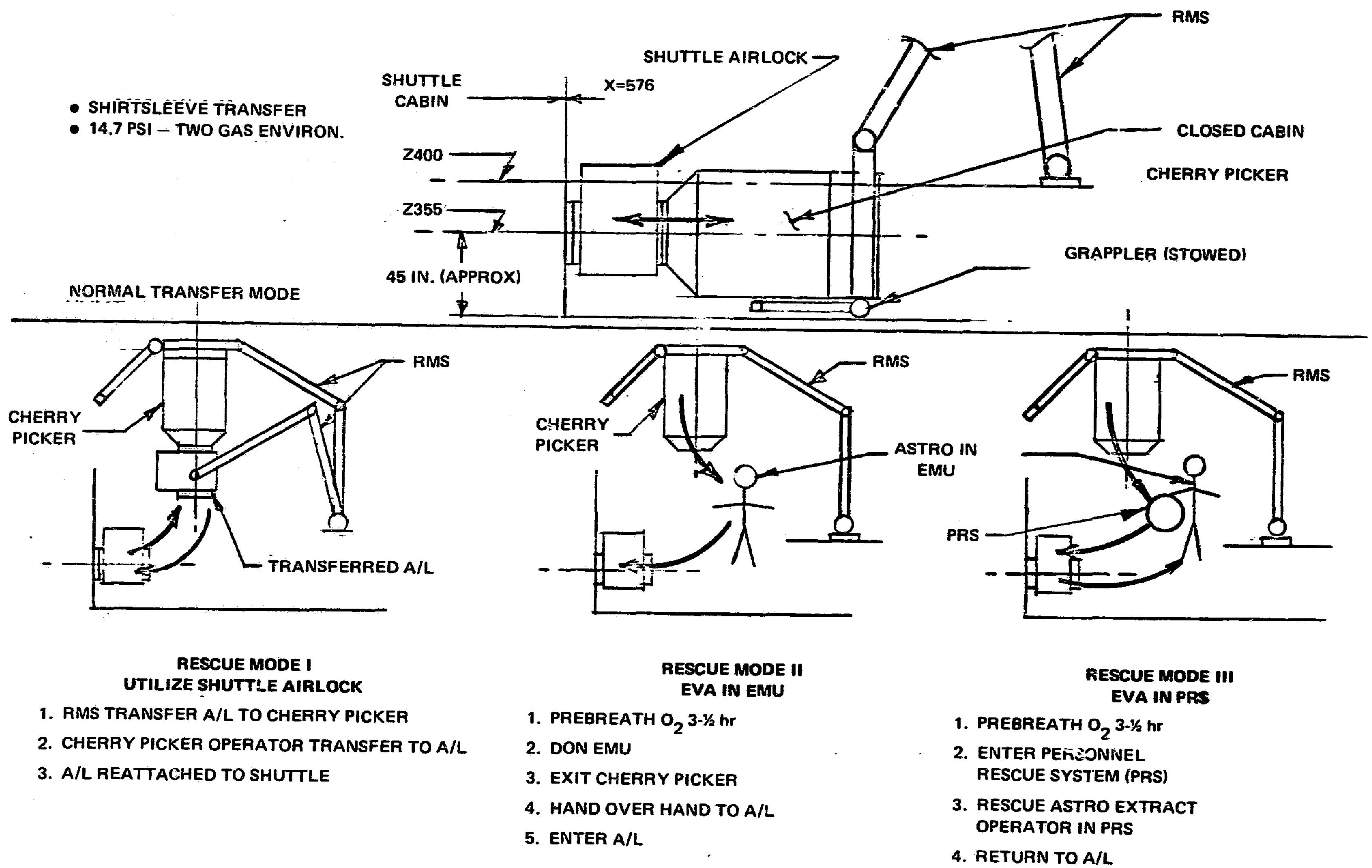

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Figure. 36. Trade - Airlock - IVA Versus EVA Vehicle Transfer Mid-Term Mission (with Shuttle)

- o Shuttle airlock is existing hardware, no weight penalty for rescue provisions
- o Shirtsleeve rescuer can be transported inside of airlock to cherry picker, thereby providing assistance to disabled operator

- Con o Shuttle airlock must be designed to be self sufficient and easily separated from cabin
  - o Size of airlock may prevent it from berthing to disabled cherry picker
  - o Airlock has to be installed in payload bay for all cherry picker missions

- Rescue Mode II - In this mode, an EMU is stored on board the cherry picker. In an emergency situation, the operator pre-breathes for $3\frac{1}{2}$ hr, dons the EMU, pressurizes the suit, opens the overhead hatch, and crawls back to the Shuttle airlock. The pros and cons of this approach are:
  - Pro o Can utilize state of the art EMU's
    - o Simplest method (does not need a rescue astronaut)
    - o Disabled operator can extract himself from tight areas
  - Con o Cabin has to be enlarged to store EMU
    - o $3\frac{1}{2}$ hr of pre-breathing required
    - o Astronaut does not have any positive means of returning to airlock
    - o If operator in cherry picker is disabled, it will require a fully suited EVA astronaut to rescue him. The suited Astronaut cannot open the hatch unless operator is fully suited

- Rescue Mode III - In this mode, a Personnel Rescue System (PRS) is stored on board the cherry picker. In the rescue mode, the operator must pre-breath for $2\frac{1}{2}$ hr and then enter the PRS, seal it, and then inflate it to 5 psia. An EVA rescue astronaut must open the hatch and extract the operator in the PRS. The rescue astronaut traverses the distance back to the airlock using an MMU for propulsion through space. The pros and cons of the approach are:

- Pro
  - o PRS storage volume smaller than EMU
  - o Operating pressure of PRS greater than EMU, therefore pre-breathing time is decreased
- Con
  - o Cabin has to be enlarged to store EMU
  - o Entering PRS unaided will be extremely difficult
  - o $2\frac{1}{2}$ hr of pre-breathing required
  - o Cabin central aisle will have to be widened to accommodate inflated PRS
  - o EVA rescue astronaut has a difficult task in extracting operator in PRS.

2.2.5.2 Closed Cabin Cherry Picker Operating from SCM or SPS - The rational used for the closed cabin cherry picker operation from the Shuttle RMS can be applied for these missions. Figure 37 depicts a two-man airlock berthed to the SCM or SPS. During an emergency, the crane arm transfers the airlock to the disabled cherry picker and berths with it. The operator in the cherry picker transfers into the airlock and is then transported back to the berthing port on the SCM or SPS. The entire rescue operation is performed in a 14.7 psi shirtsleeve atmosphere. There is no need to stow an EMU or PRS in the cherry picker. The rescue time is minimized with the elimination of pre-breathing requirements.

2.2.5.3 Crane Turret Intravehicular Transfer - The crane turret MRWS is permanently attached to the SCM or SPS. Normal and emergency transfer between vehicles is in a shirtsleeve attire as shown in Figure 37.

2.2.5.4 Free Flyer - The free flyer MRWS is contemplated for the far-term missions such as SPS. It is assumed that numerous free flyers will be operating in the large structural buildup in space. As such, if a free flyer is disabled, a second free flyer will be dispatched to dock with it and perform rescue transfer to the operational free flyer. This mode dictates that the cabin of a free flyer be sized for at least two occupants (Option 3 in Figure 29). Figure 38 depicts a rescue scenario of a disabled free flyer.

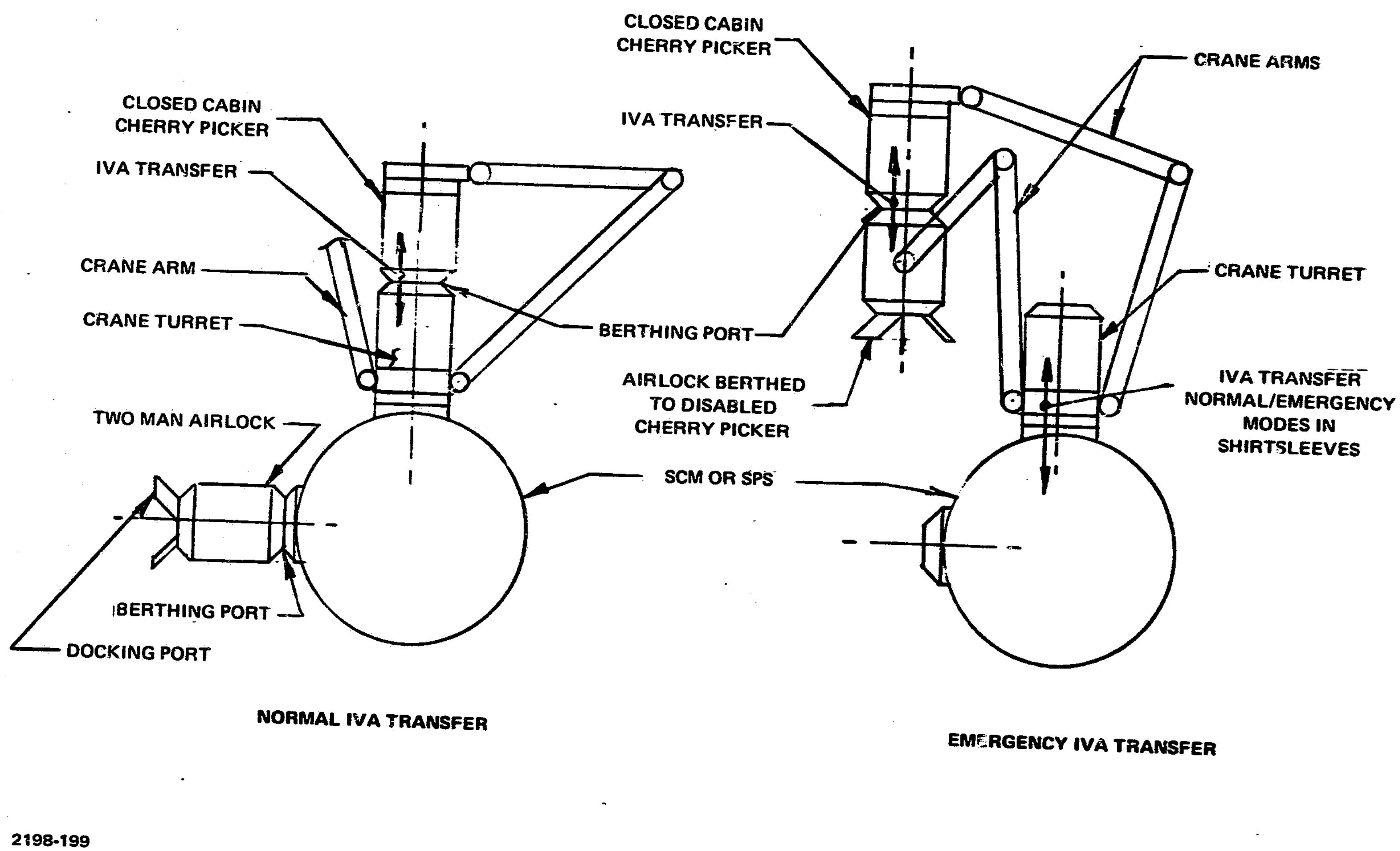

Figure 37. Mid-Term/Far-Term Mission -- Crane Turret

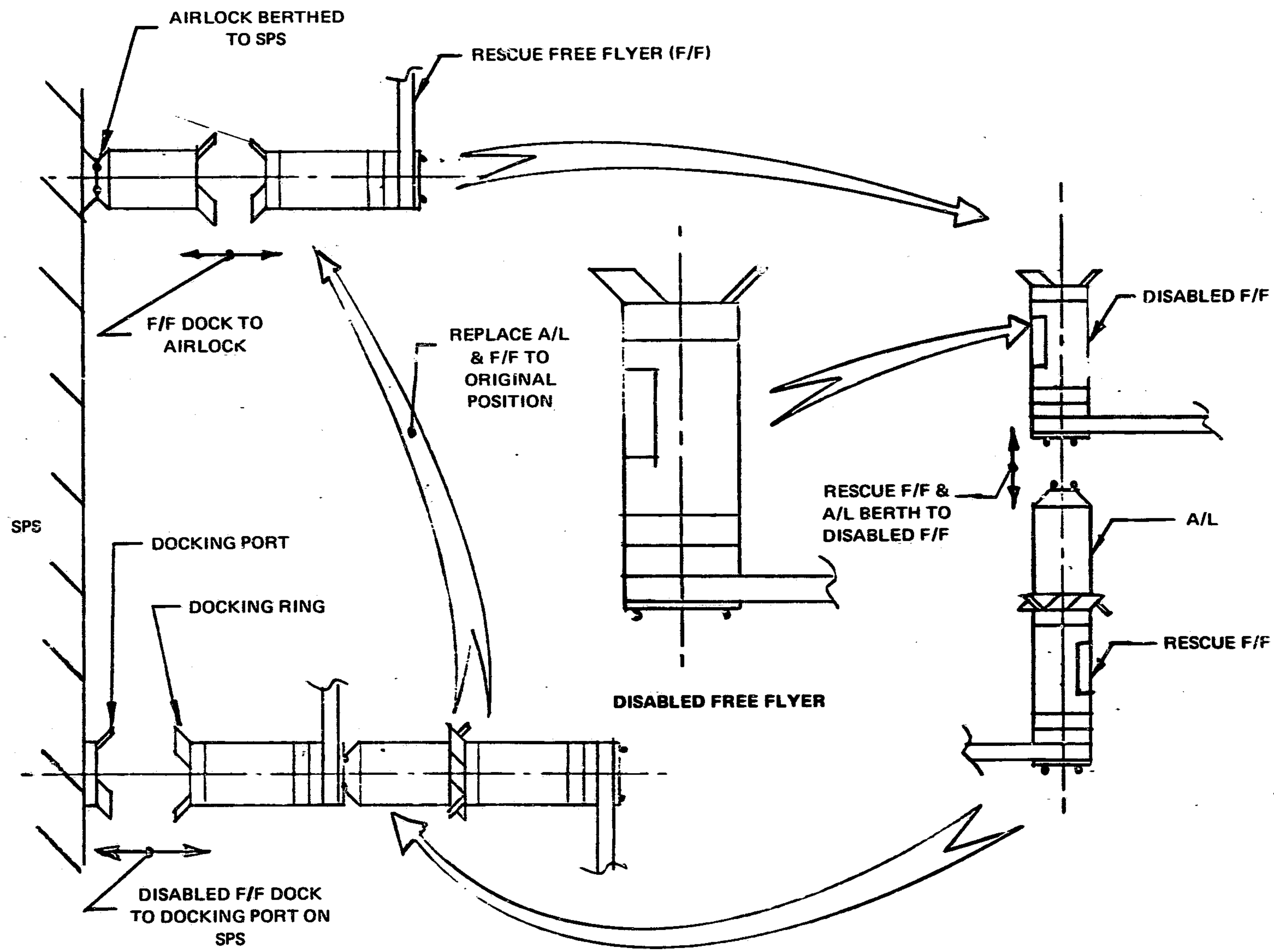

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Figure 38. Rescue of Disabled Free Flyer Using Two-Man Airlock

2.2.5.5 POTV - The same analogy applies to the POTV as the free flyer. Rescue will be shirtsleeve transfer between the disabled and rescue vehicle. Again, the MRWS cabin should be sized for two people.

2.2.6 Subsystem Location - Inside versus Outsize versus Mix

A list of components of the various subsystem required was compiled. In order to hold cabin volume and heat load to a minimum, and ease the maintainability and servicing task, various components were located external to the cabin in the aft equipment bay. Only those components, the functional requirements of which necessitated their location in the cabin, were located there (example: cabin fan). Table 14 lists the various components, their location, and weight for the closed cabin MRWS. Approximately 1 cu m of volume is required for the aft equipment bay.

2.2.7 Design Load Definition

2.2.7.1 Requirements -

- Factors of safety
  - Primary structure

    Yield Load - 1.2 X limit load

    Ultimate Load - 1.5 X limit load
  - Cabin pressure structure

    Ultimate Load - 2.0 X max relief valve pressure
  - Windows, doors, hatches

    Ultimate Load - 2.0 X max relief valve pressure
  - Tankage

    Ultimate Load - 2.0 X max relief valve pressure
- Scatter factor = 4.0 on service life
- Cabin pressure = 14.7 psi nominal
- Service usage life = 10 yr.

TABLE 14
EQUIPMENT LOCATION AND WEIGHT SUMMARY
(Sheet 1 of 2)

EQUIPMENT	LOCATION			WEIGHT (lb)
	CABIN	EXTERNAL	AFT BAY	
ECLS				(437)
• O_2 TANK/REGULATOR/VALVES			●	43
• N_2 TANK/REGULATOR/VALVES			●	44
• EMERG O_2 TANK/REG/VALVES			●	6
• CABIN RELIEF VALVE	●			2
• CONDENSATE FAN/PUMP	●			27
• CONDENSATE STORAGE TANK	●			4
• AVIONICS COOLING	●	●	●	35
• CABIN FAN	●			14
• CABIN HEAT EXCHANGE	●			50
• HEAT EXCH COOLANT PUMP	●			10
• HEAT EXCH TEMP VALVE	●			6
• RADIATOR		●		100
• FOOD/DRINKING WATER	●			5
• WASTE DISPOSAL	●			5
• PLUMBING/DUCTING	●	●	●	20
EPS				(209)
• EMER BATTERY			●	135
• INVERTOR			●	20
• CONTROL/DIST. BOX			●	4
• REGULATOR			●	10
• WIRING	●	●		40
COMMUNICATIONS				(62)
• VHF RECEIVER			●	10
• VHF TRANSMITTER			●	10
• SIGNAL PROC EQUIP			●	15
• RANGE TONE TRANSFER ASSY			●	10
• ANTENNA		●		14
• MICROPHONE/HEADSET	●			3

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TABLE 14

EQUIPMENT LOCATION AND WEIGHT SUMMARY

(Sheet 2 of 2)

EQUIPMENT	LOCATION			WEIGHT
	CABIN	EXTERNAL	AFT BAY	(lb)
INSTRUMENTATION				(76)
• SIGNAL COND UNIT			●	35
• PULSE CODE MOD/TIMING			●	23
• CAUTION/WARNING ASSY			●	18
DEXTEROUS MANIPULATOR				(320)
• ARMS (2)		●		300
• DRIVE ELECTRONICS			●	20
CCTV				(55)
• CAMERA (2)		●		15
• ELECTRONICS			●	20
• BOOM (2)		●		20
ILLUMINATION				(30)
• LIGHTS (2)		●		20
• CONTROL BOX	●			10
GRAPPLER				(170)
• ARM (1)		●		150
• DRIVE ELECTRONICS			●	20
TOOLS				(100)
• VARIOUS TOOLS		●		100
CONTROLS/DISPLAYS				
• SEE SUBSECTION 2.5	●			(250)

CLOSED CABIN TOTAL WEIGHT = 1709 lb

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2.2.7.2 Launch and Landing Operations Mounted in Orbiter Payload Bay -

- Design will comply with requirements of Payload Accommodation Document JSC 07700 Vol. XIV
- Flight limit acceleration loads given in Paragraph 1.2.3 will be used until coupled payload/orbiter analyses are performed.

2.2.7.3 Space Operations Loads -

- Cabin pressure 14.7 psi ultimate
- Docking/berthing TBD
- Loads induced by RMS/robust arm motions TBD
- Equipment handling TBD.

2.2.7.4 Materials - The various materials applications will be selected for structural efficiency, outgassing and flammability criteria, and other environmental requirements.

2.2.8 Pressure Vessel Construction Technique and Load Paths/Service Life

One of the more significant problems associated with the closed cabin cherry picker is the design and service life evaluation of the structure. This section discusses the issues, some potential solutions, methods of analyses, and the future work required in these areas.

2.2.8.1 Pressure Vessel Construction Techniques and Load Paths - The closed cabin shell structure will be sized for 2024-T851 aluminum machined skins over machined frames of the same alloy. Trade studies carried out on previous vehicles have shown that integrally stiffened machined skins over machined frames are preferred in order to reduce the number of attachment penetrations. In those areas requiring mechanical fastening, the frames are attached to the skin with "O" ring rivets and faying surface adhesive. These cabin sealing techniques were proven effective on the Lunar Module Cabin. At the transition cross sections where diameter changes occur, machined frames will be used to provide continuous structural load paths. Hard points should be provided for concentrated loads induced by mass attachments, manipulator arms cabin attachment to the robust arm etc. The required strength and stiffness for these support points should be provided.

Particular attention should be given to the windows and hatches. The window will have three plies: an outer fused silica pane for thermal and micrometeroid protection and the middle and inner redundant plies of chem-tempered glass.

2.2.8.2 Service Fatigue Life - The fatigue life of the close cabin cherry picker structure should be assessed for service usage of 10 yr with a scatter factor of 4.0. The structure will be a safe-life design with incorporation of fail-safe features by providing adequate fracture-arrest capability and residual strength in any potential damaged condition. The fatigue spectra should include cabin pressure and applied external load cycles which may be experienced during the life of the cherry picker. The fatigue analysis should be carried out on various methods of construction to obtain the most efficient structure that will meet the requirements, including:

- External skin supported by frames and hat section stiffeners
- External skin stiffened by continuous corrugated sheet and frames
- Honeycomb with frames
- Integrally stiffened skin in a waffle grad pattern (The latter is the perferred configuration).

The windows which will be made of chem-tempered glass should also be evaluated for the cabin pressure cycling to verify the required service life.

2.2.8.3 Fracture Mechanics Analysis - The effects of flaws and defects on the structure depend on a prior assessment of potential flaw sizes, types, and locations that can reasonably be expected to remain undetected by the best available NDE techniques. The degradation of the required service life of such initial flaws will be avoided by:

- Providing a flaw tolerant design
- Using the inherent fracture resistance of thin sheet materials such as 2024-T81 sheet or 2024-T851 plate. For example, 2024-T81 sheet has a favorable ratio of plane stress fracture toughness ($K_c = 55$ ksi $\sqrt{\text{in.}}$) to tensile yield strength ($F_{ty} = 55$ ksi)
- Designing for reduced stress levels in fracture critical areas
- Performing fracture mechanics analyses based on sustained and cyclic loads

- Fracture mechanics analyses will also be carried out on all pressurized tankage
- The analyses will also establish the proof test requirements.

2.2.9 Radiation Protection Issues

A preliminary study has been made to assess the radiation protection for the crew in the open and closed cabin cherry pickers for the missions and orbits given in Table 15 which include low earth orbits and geosynchronous orbits. The environment models considered were trapped radiation, galactic cosmic rays and solar flare radiation. The allowable dose limits used are shown in Table 16.

In summary, the closed cabin can be designed to provide adequate protection at LEO and GEO except for solar flare events in which case a "storm shelter" must be provided aboard the main base to which the crew can retreat. The open cabin system could be used in LEO provided the crew does not work during passage through the South American Anomaly because the Shuttle suit does not provide sufficient protection. This precludes work periods during approximately 30% of the orbit which is not desirable. In addition, the open cabin cannot be used in GEO. It is recommended that for the above reasons the configuration design be limited to the closed cabin. Additional benefits include higher crew productivity because of the shirtsleeve work environment and the development of a more versatile cherry picker system which is not orbit limited.

2.2.9.1 Design Approaches -

Low Earth Orbit - Closed Cabin

Figure 39 presents the trapped radiation dose plots for skin, eye, and blood forming organs as a function of orbit inclination and altitude for a wall thickness of 0.1 in. The eye and skin dosages are approximately the same for some upper altitudes and inclination combinations. The calculations were subsequently confined to skin dose because it is close to the limit for the eyes and is more difficult to shield.

Figure 40 shows the daily skin dose received as a function or orbit inclination, altitude, and cabin wall thickness. For all the LEO 28.5 degree missions of Table 15, for example, a typical wall thickness of 0.075 in. of aluminum is well below the allowable daily dose for the 30-day mission duration. For the LDEF mission in a

TABLE 15

CANDIDATE MISSIONS MRWS

	MISSION	ORBIT	MRWS		hr/SHIFT	NO. OF SHIFT
			OCP	CCP		
NEAR-TERM	MMS	$28.5^{\circ} - 57^{\circ}$ @ 500 – 1600 km	X		6	2
	LDEF	$28.5^{\circ} - 57^{\circ}$ @ 560 km	X		6	4
	LSS		X		6	2
	SCAFE		X		6	8
MID-TERM	TA-1	28.5° @ 400 km	X		6	25
	TA-2	28.5° @ 400 km	X		6	29
	RADIOMETER	28.5° @ 350 km		X	8	102 @ 2/day
	PSP	28.5° @ 350 km		X	8	25 @ 2/day
	POTV			X	8	
FAR-TERM	SPS	LEO – 31° @ 478 km		X	10	108 @ 2/day
		GEO		X	10	

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TABLE 16

ALLOWABLE DOSE LIMITS

	PRIMARY REFERENCE RISK	ANCILLARY REFERENCE RISK		
	(5 cm)	BASE MARROW (5 cm)	SKIN (0.1 mm)	LENS & EYE (3 mm)
1-yr AVERAGE DAILY RATE		0.2	0.6	0.3
30-day MAXIMUM		25	75	37
QUARTERLY MAXIMUM*		35	105	52
YEARLY LIMIT		75	225	112
CAREER LIMIT	400	400	1200	600

* MAY BE ALLOWED FOR TWO CONSECUTIVE QUARTERS FOLLOWED BY 6-mo RESTRICTION TO STAY WITHIN YEARLY LIMIT

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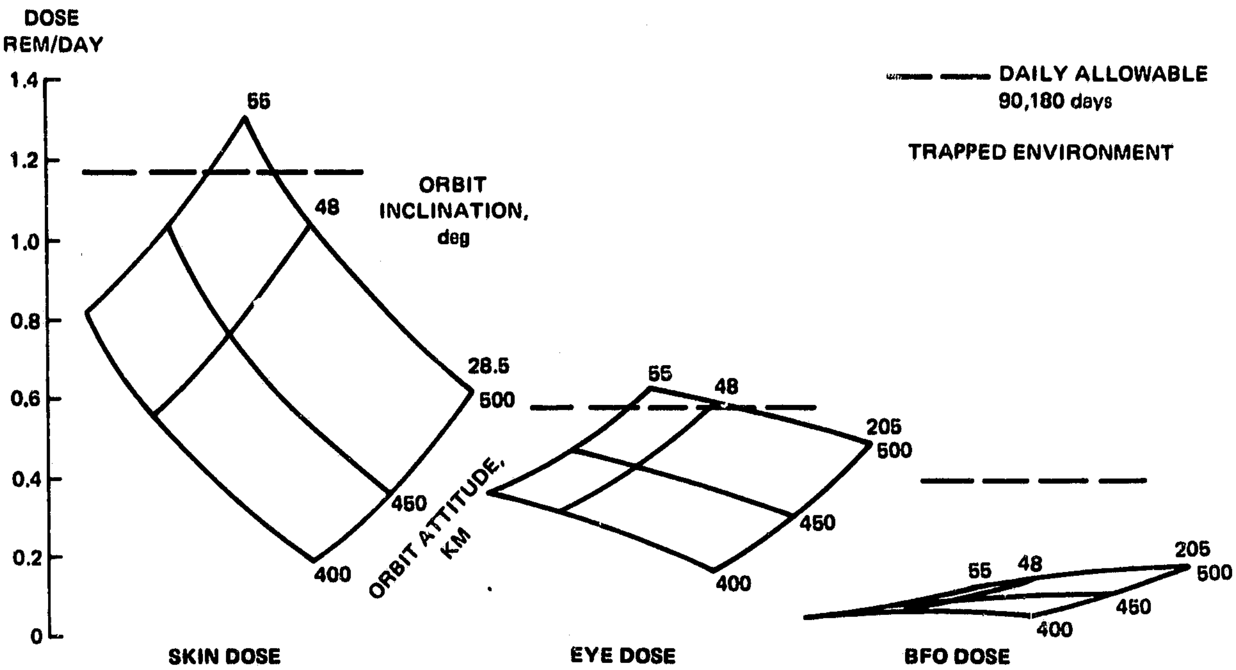

Figure 39. Module Radiation Dose — 0.1 Inch Wall Thickness

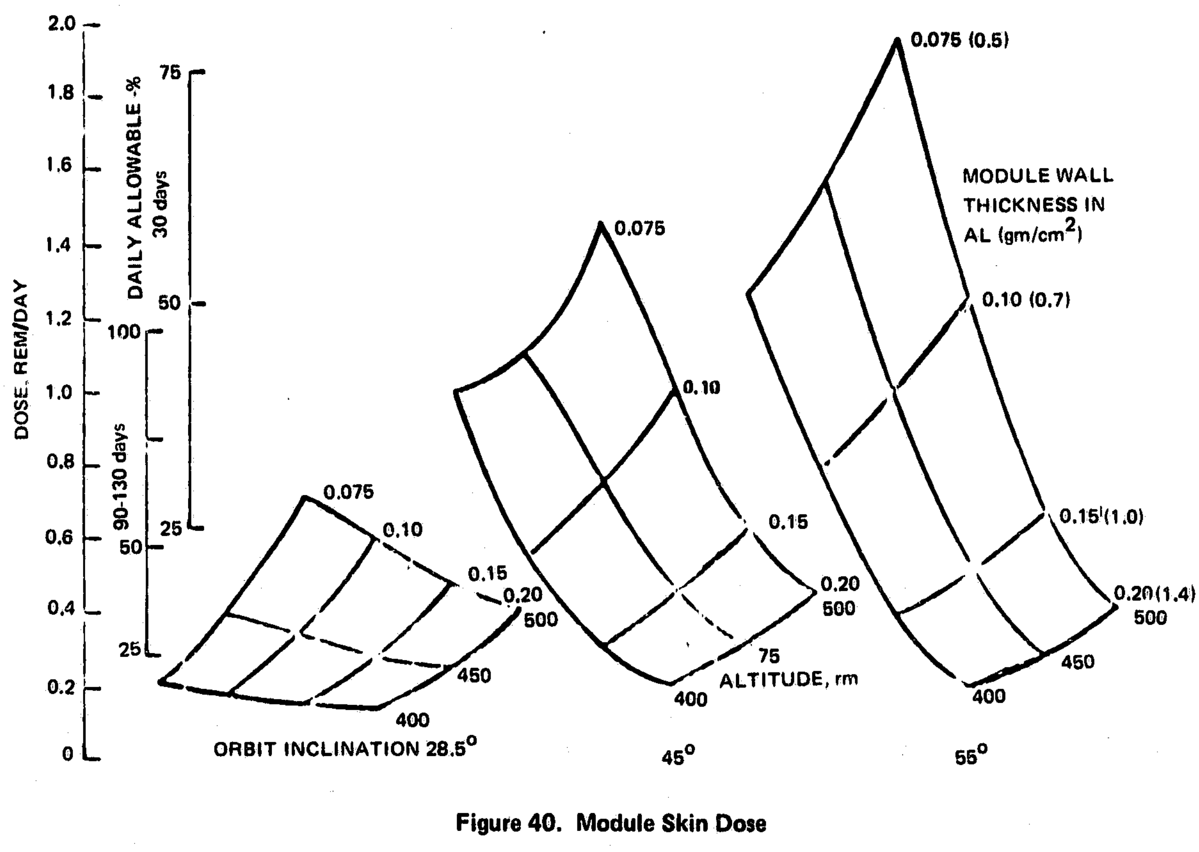

Figure 40. Module Skin Dose

57 degree at 560 km, the wall thickness of 0.10-in. aluminum would permit exceeding the allowable for the 90 - 180 day mission; the same thickness would permit a dose of approximately 50% of the allowable for the 30-day mission. Based on these data, it appears that the closed cabin can be designed to limit the dose for any of the missions in low earth orbit.

Low Earth Orbit - EVA/Open Cabin

Restrictions on EVA in low earth orbits are caused primarily by the energetic trapped proton environment in the South Atlantic Anomaly. With a 30-degree inclination orbit, the anomaly is traversed in only 30% of the orbit, so that there are daily periods of about 16 hr during which EVA's can be routine. Figure 41 shows the daily allowable dose for various inclination altitudes, daily EVA shift duration, and EVA suit thicknesses. The data is based on assuming no EVA during passages through the South Atlantic anomaly. The data shows that for the 28.5-degree inclinations, the Shuttle EVA suit thickness (0.1 gm/cm^2 thickness) and a maximum required daily shift of 8 hr, the dose received at 500 km is less than 20% of the allowable. Therefore, the EVA can be accomplished with a Shuttle EVA suit for the 28.5-degree missions providing no activity takes place during traverse of the South American Anomaly. At the 55-degree inclination and 500 km for the 6-hr shift, the dose received during EVA would be approximately 60% of the allowable. For this, mission consideration should be given to using a thicker suit for the 57° at 560 km.

During solar flare activity, an advanced warning system must be developed to permit the crew to re-enter the base in order to enter the "storm shelter" which must be provided for such an event. This type of protection must be available to the closed cherry picker concept also; the necessary wall thickness required for solar flare protection would make the cherry picker excessively heavy.

Geosynchronous Orbit

The higher dose rates in geosynchronous orbit are caused by the higher intensity electron and associated bremsstrahlung environment and the effective absence of geomagnetic shielding against solar flare particles and cosmic rays.

Figure 42 shows the dose rate per day versus aluminum shielding thickness for trapped electrons and bremsstrahlung. These data are based on the 56-day Skylab mission with operational limits for 56 days of 250 rem skin dose and 25 rem to

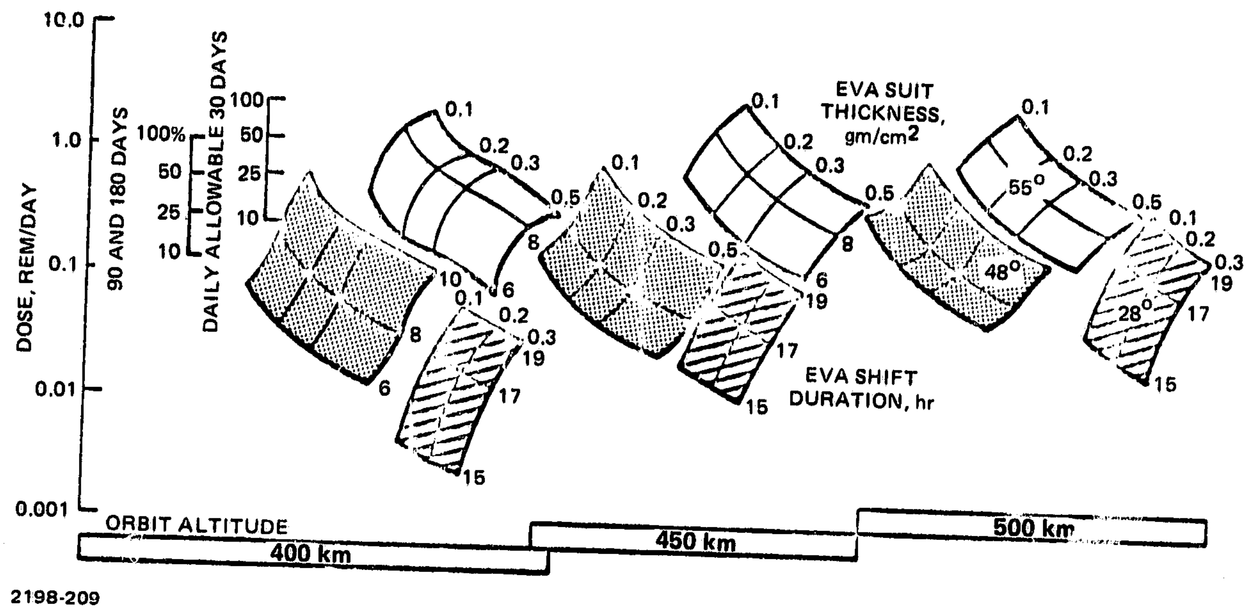

Figure 41. EVA Daily Skin Dose

OPTION	SUIT SHIELDING THICKNESS, in. (0)	CABIN SHIELDING THICKNESS, in.
A	0.22 ALUM	0.22 ALUM
B	0.12 ALUM	0.40 ALUM
C	0.11 ALUM	0.40 ALUM + 0.02 TANTALUM

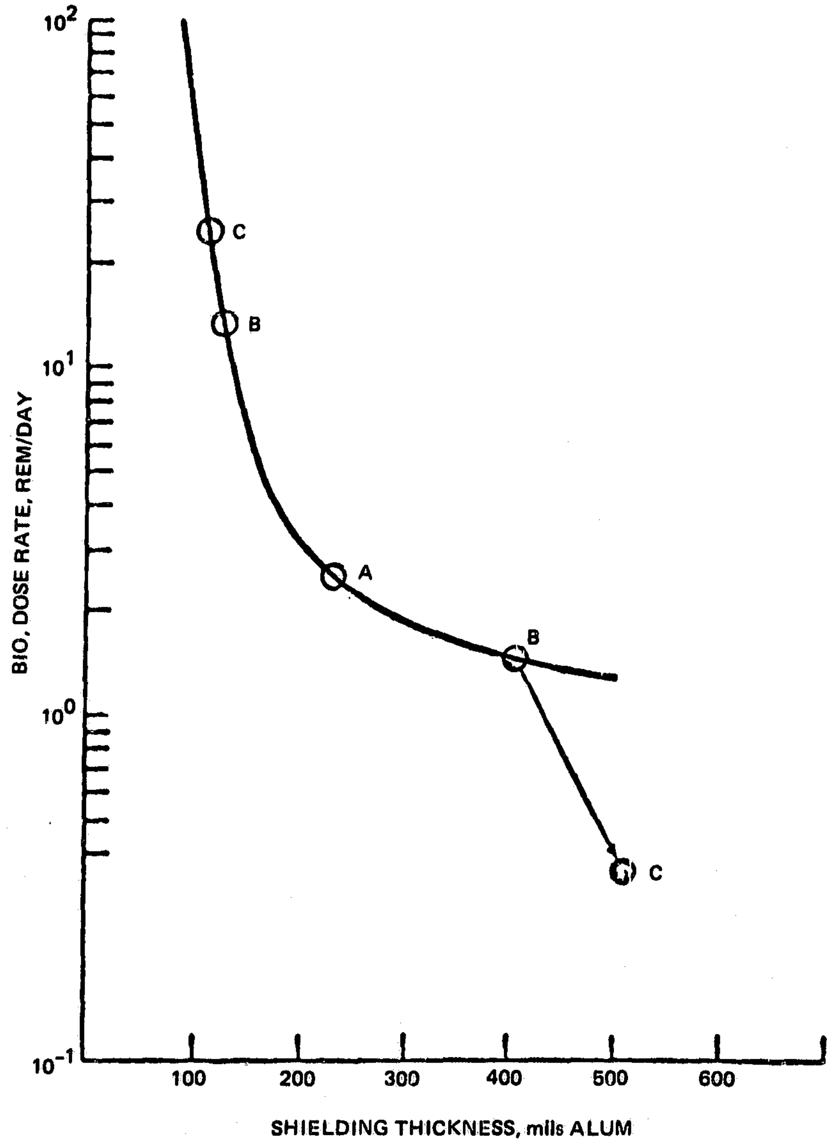

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Figure 42. Average Biological Radiation Doses in Geosynchronous Orbits (Trapped Electrons & Bremsstrahlung)

bloodforming organs. Allowances must be made for extrapolating these limits to GEO operations. The figure also includes dose rate per day for suit shielding and in addition the protection afforded by combining aluminum with the refractory metal tantalum. The estimated allowable daily dose is 2.15 rem. The data show that EVA suit does not provide sufficient protection; the aluminum cabin shielding required is approximately 0.30-in. thickness. The curve from point B to C shows the increased protection provided by combining layers of aluminum and tantalum shielding. Further analyses are required to optimize the thickness requirement for the cabin wall. For solar flare incidents a "storm shelter" aboard the main base should be provided.

2.2.9.2 Conclusions and Recommendations

- Low Earth Orbit
  - Radiation level is low
  - Open cabin operation/EVA practicable
  - Avoid open cabin operation during passage through South Atlantic anomaly
  - Need "Storm Shelter" during Solar Flares
- Geosynchronous Orbit
  - Re-examine Biological Dose Limitations
  - Radiation Level Manageable for Close Cabin Design
  - Open Cabin Operation/EVA should be avoided
  - Need "Storm Shelter" during Solar Flares
- References
  - Space Station System Analysis Study. NAS-9-14958, July, 1977.
  - AIAA/MSFC Symposium on Space Industrialization. May 26, 27 1976.

2.2.10 Meteoroid Protection Issues and Recommendations

An evaluation of meteoroid protection requirements was made using the preliminary design average total meteoroid environment of NASA TMX 64627. The average environment includes the average sporadic plus a derived stream flux. These data include:

- Particle density 0.5g/cm^3
- Average velocity 20 km/sec^2

- Flux model

$$10^{-6} \leq m \; 10^{0}, \; \log N_t = -14.27 - 1.213 \log m$$

$$10^{-12} \leq m \; 10^{-6}, \; \log N_t = -14.37 - 1.584 \log m - 0.063 (\log m)^2$$

where N_t = number of particles per m^2 per second of mass m or greater.

The defocusing factor for earth G_e was assume equal to one. Figure 43 shows the bumper shield thickness required versus probability of meteoroid encounter per square meter for various times of exposure. The results show that a bumper shield design concept using a thickness of 0.019 in. gives a reliability of survival of 0.9999 where R_e = (1 - Pe) for 10 yr of exposure. A more detail analysis is required for the actual cabin design considering radiation wall thickness protection and other shielding requirements.

In addition, the open cabin design wherein the EVA suit will provide the primary protection during the mission exposure durations must be evaluated in further detail considering the duration of exposure and the capability, if any, of EVA to provide sufficient protection.

References

- Space and Planetary Environment Criteria Guidelines. NASA TM X64627, 1971 Revision.
- Meteoroid Damage Assessment. NASA SP-8042.

2.2.11 Radiator - Integral with Structure versus Separate Installation

Evaluation

- Rejection of the heat load from the pressurized MRWS cabin requires a radiator because use of consumables (4.5 to 5.0 lb/hr of water in a boiler or sublimator) is impractical. Current radiator design indicates a required surface area of 80 - 90 ft^2 for the MRWS, depending on window area
- A further consideration for radiator installation is the requirement for coolant circulation through the radiator with fluid interconnections into the cabin

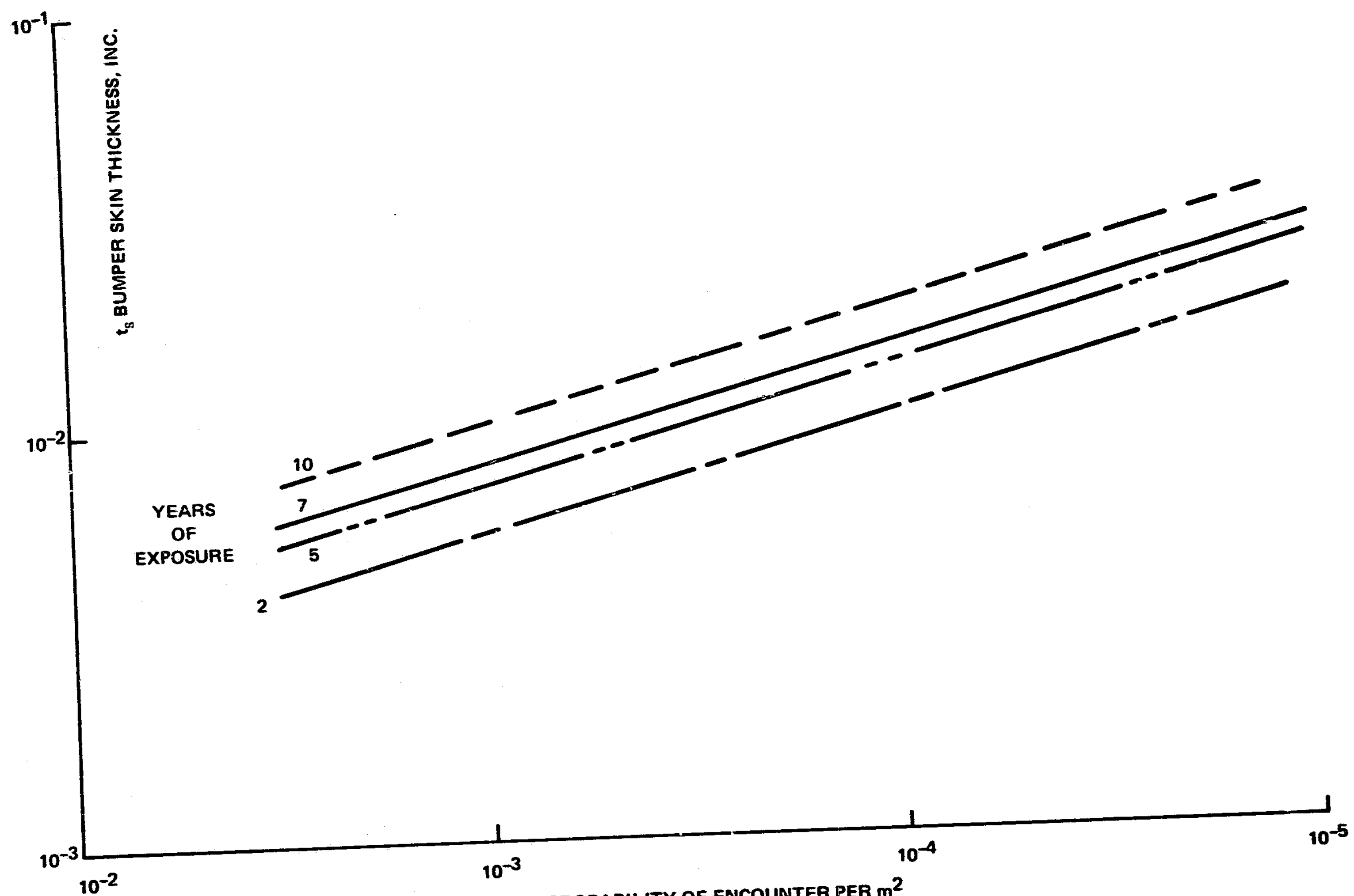

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Figure 43. Probability of Meteoroid Encounter per Square Meter Versus Bumper Shield Thickness

- **Because the radiator assembly requires local stiffness to maintain integrity and form factor, the preferred method of radiator installation consists of standoffs from the surface of the MRWS cabin (Figure 44a)**
- **An alternate radiator installation (Figure 44b) consists of a cantilevered arrangement with dual-faced radiation surface. This radiator configuration and resultant, MRWS deployment considerations require further evaluation.**

Recommendation

It is recommended that the radiator structure should be integral with the MRWS cabin.

2.2.12 MRWS - Growth Trade

Using Option 1 as the baseline configuration for the closed cabin cherry picker, (Figure 45), a study was made to determine the growth capability into future MRWS vehicles. The CCP was broken down into six basic structural/functional elements: upper mating interface, cabin core with hatches, rotary bearing, stabilizer base/ crane turret, and lower berthing interface.

The cabin core structure was considered common to the CCP, crane turret MRWS, free flyer MRWS, and POTV airlock. The cabin core provides the structural elements common to all four MRWS vehicles such as pressure shell, windows, hatches, console support structure, flooring, restraint system platform and mounting provisions for externally mounted equipment. The CCP and crane turret MRWS have a berthing port interface added to the top of the cabin core, while the free flyer and POTV MRWS vehicle have a docking ring interface added. All four vehicles have identical rotary bearing and lower berthing interfaces added to the bottom region of the cabin core. The CCP, free flyer and POTV MRWS vehicles have the stabilizer base installed between the rotary bearing and berthing interface, while the crane turret MRWS has a crane turret added between the cabin core and rotary bearing.

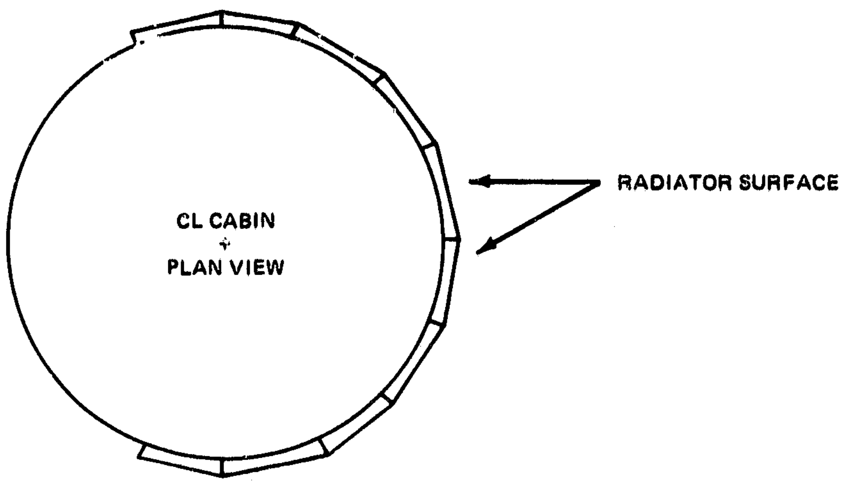
The controls and displays can be tailored to meet the requirements of each MRWS with minimum impact to the common cabin core.

2.3 MECHANICAL

2.3.1 Rotary Bearing Size

Baseline MRWS cabin design shows a secondary exit hatch located in the floor. The cabin revolves about its vertical axis by means of a rotary bearing. As stated

(a) MRWS - INTEGRAL RADIATOR



(b) MRWS - CANTILEVER RADIATOR

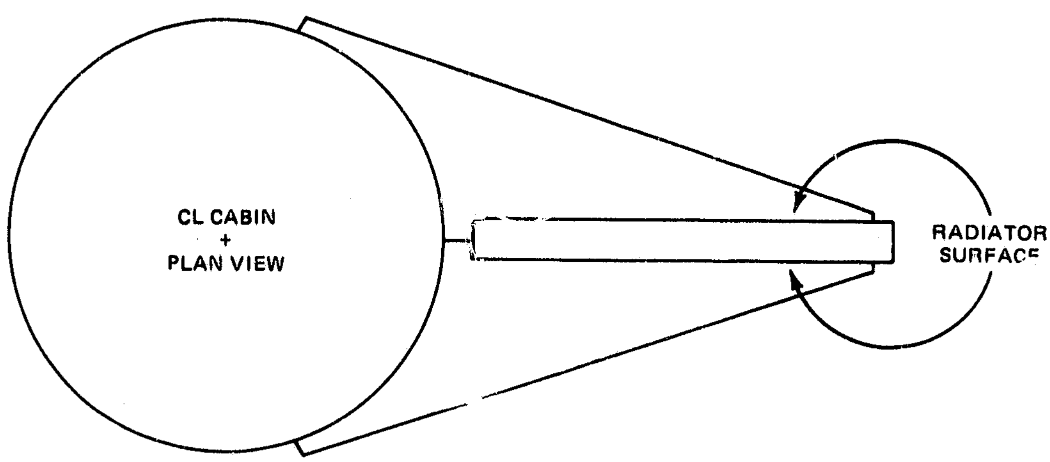


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Figure 44. MRWS Radiator Arrangement

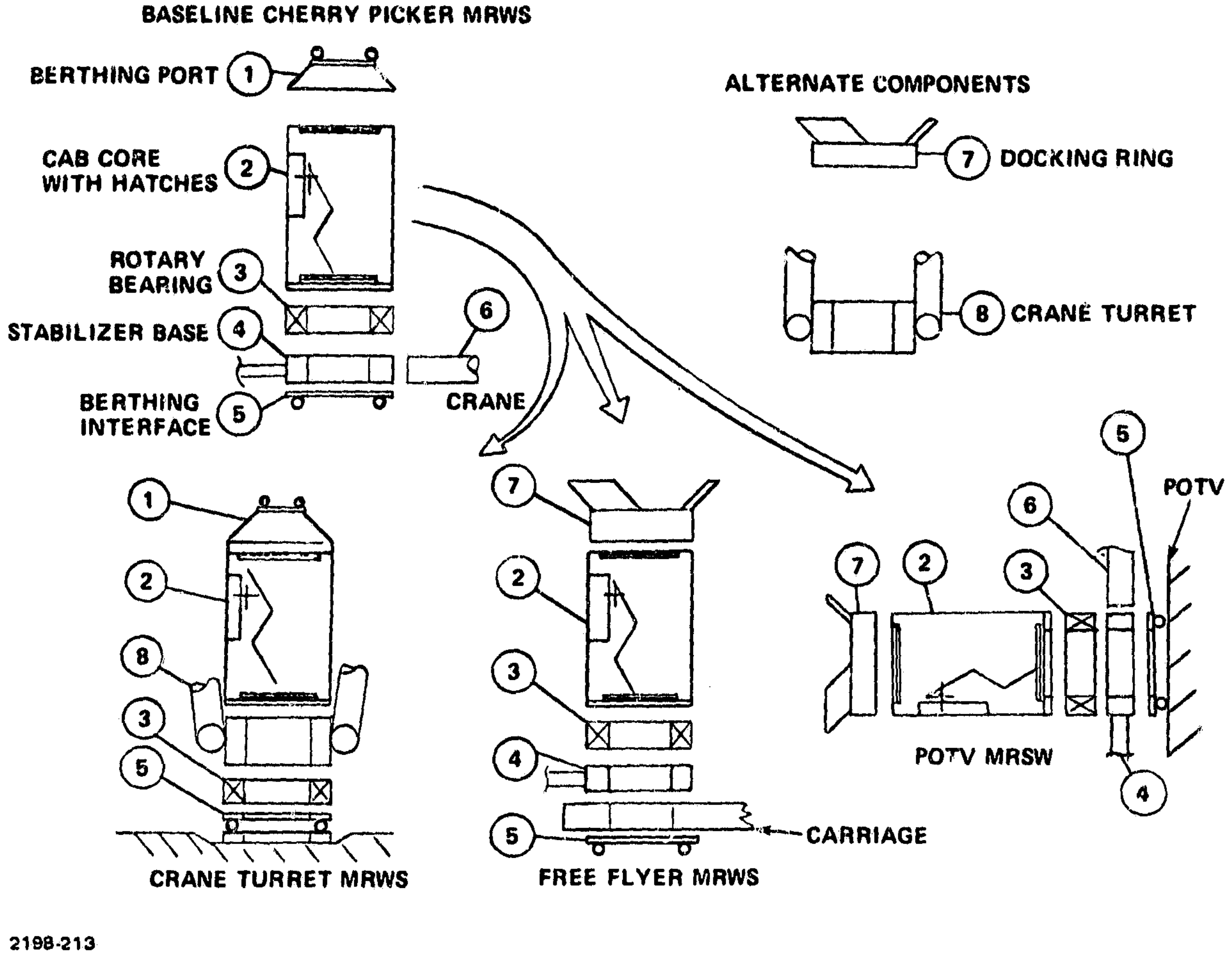

Figure 45. MRWS Future Growth Trade

in Paragraph 2.2.3, an 0.8-m diameter lower hatch is recommened. Using information from a commercial rotary bearing manufacturer (ROTEK), Figure 46 was prepared to show the weight of selected bearings for each hatch diameter. Because weight is an important factor in overall design, a strong case can be made for the smaller diameter rotary bearing.

2.3.2 Master Control Configuration

A configuration of a full reach 6 DOF plus shoulder yaw controller in lieu of a controlled volume indexed controller is shown in Figure 47. Included is the orientation of an astronaut in a zero g rest position relative to the design eye, the cabin and windows, the adjustable foot restraint platform, the master controller (one for each arm), and the maximum control volume which is restricted by Astronaut arm reach, and the cabin interior walls, consoles, etc.

Three views of the Master Controller volume capabilities with the restrictions imposed when installed in the cabin and used by the astronaut are shown in Figure 48.

It is envisioned that a four bar linkage for support of the yaw pivot will permit the astronaut to manually position and lock the pivot location for three specific reasons:

- Provide clearance for cabin hatch opening
- Provide additional room for the astronaut during free flyer operation
- Provide personalized adjustment and increased outboard reach capabilities with an off-center-line astronaut.

2.3.3 One versus Two Dextrous Manipulators

An examination of potential manipulator tasks reveals a number of activities which could be performed with a single dextrous arm. Tasks which seem to require two arms might be performed by a single arm utilizing an end effector which is dedicated to that task. A single arm on a rotating cabin MRWS can reach over the same volume as two dextrous arms. A single-arm system would save the weight and cost of a second arm. It would also reduce MRWS cost and weight by eliminating attachment and controller hardware and reducing the requirements for internal cabin volume.

OPTION	MODEL NO.	A– BEARING ID	B– HATCH SIZE	GEAR LOCATION	WEIGHT (NO.)
1	H7-38E1	0.89M (35.1 in.)	0.81 m (32.0)	EXTERNAL	290
2	H8-47E1	1.10 M (43.2 in.)	1.02 m (40.0)	EXTERNAL	690

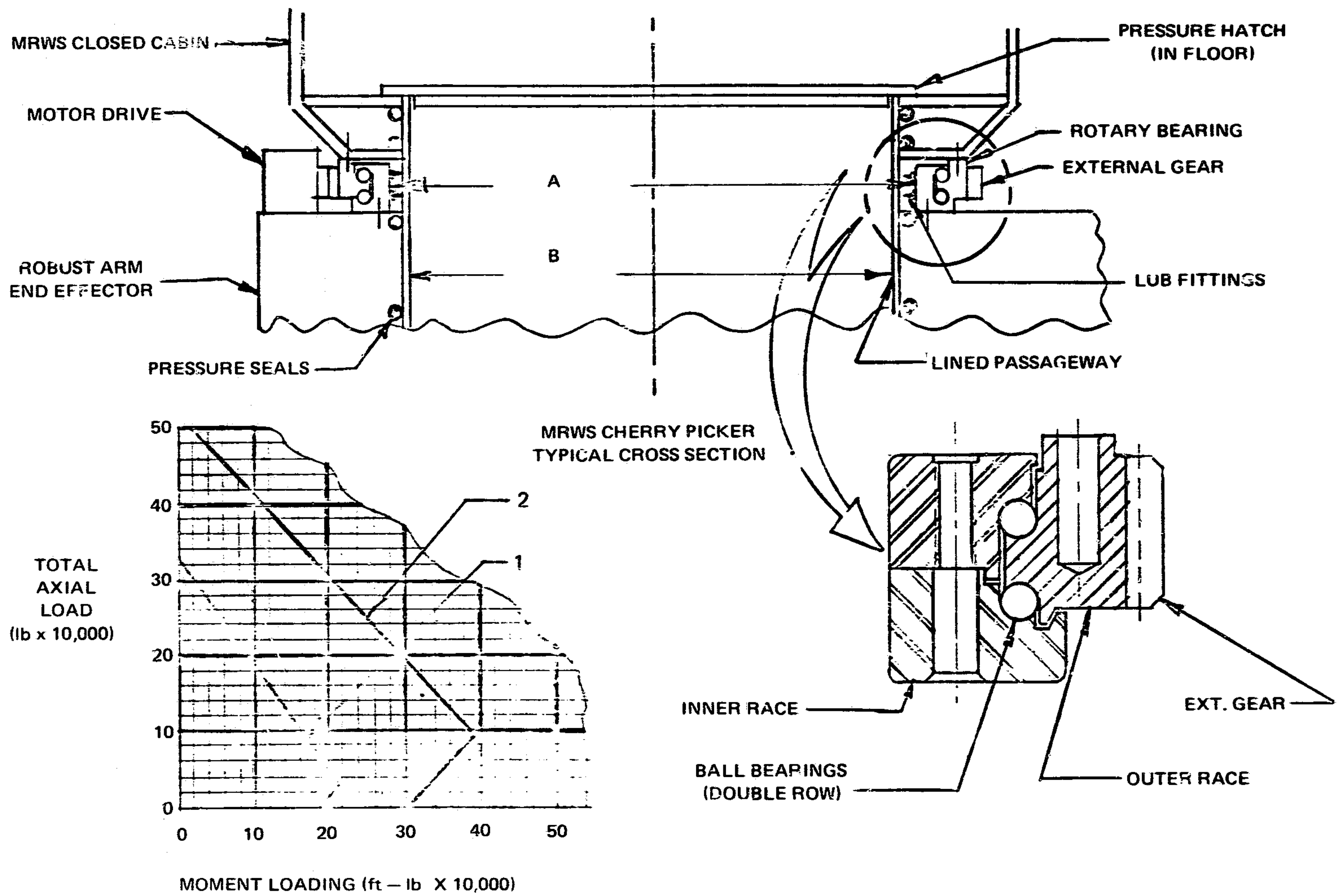

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Figure 46. Rotary Bearing – Size/Weight/Load Comparisons

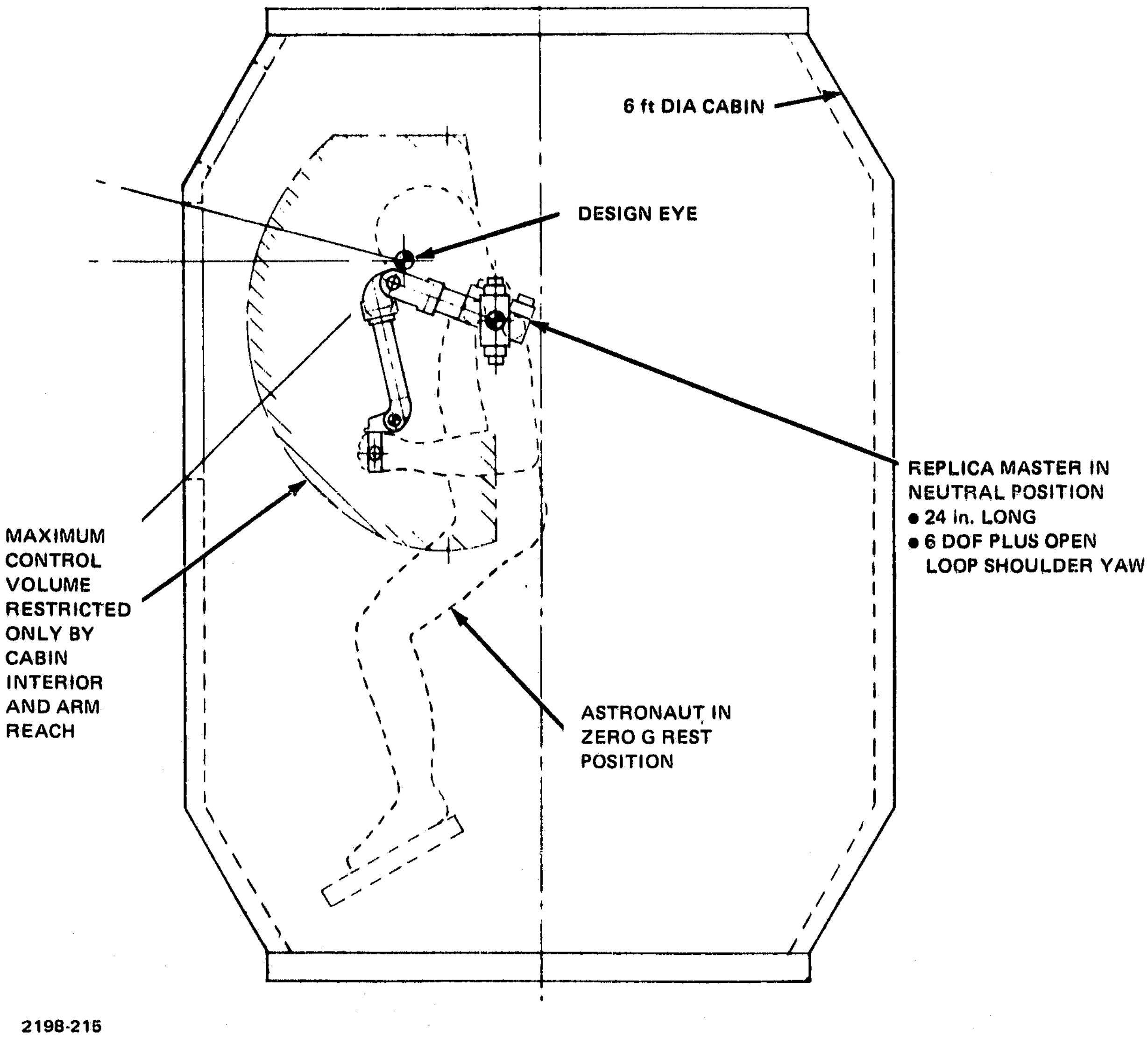

Figure 47. Master Control Configuration

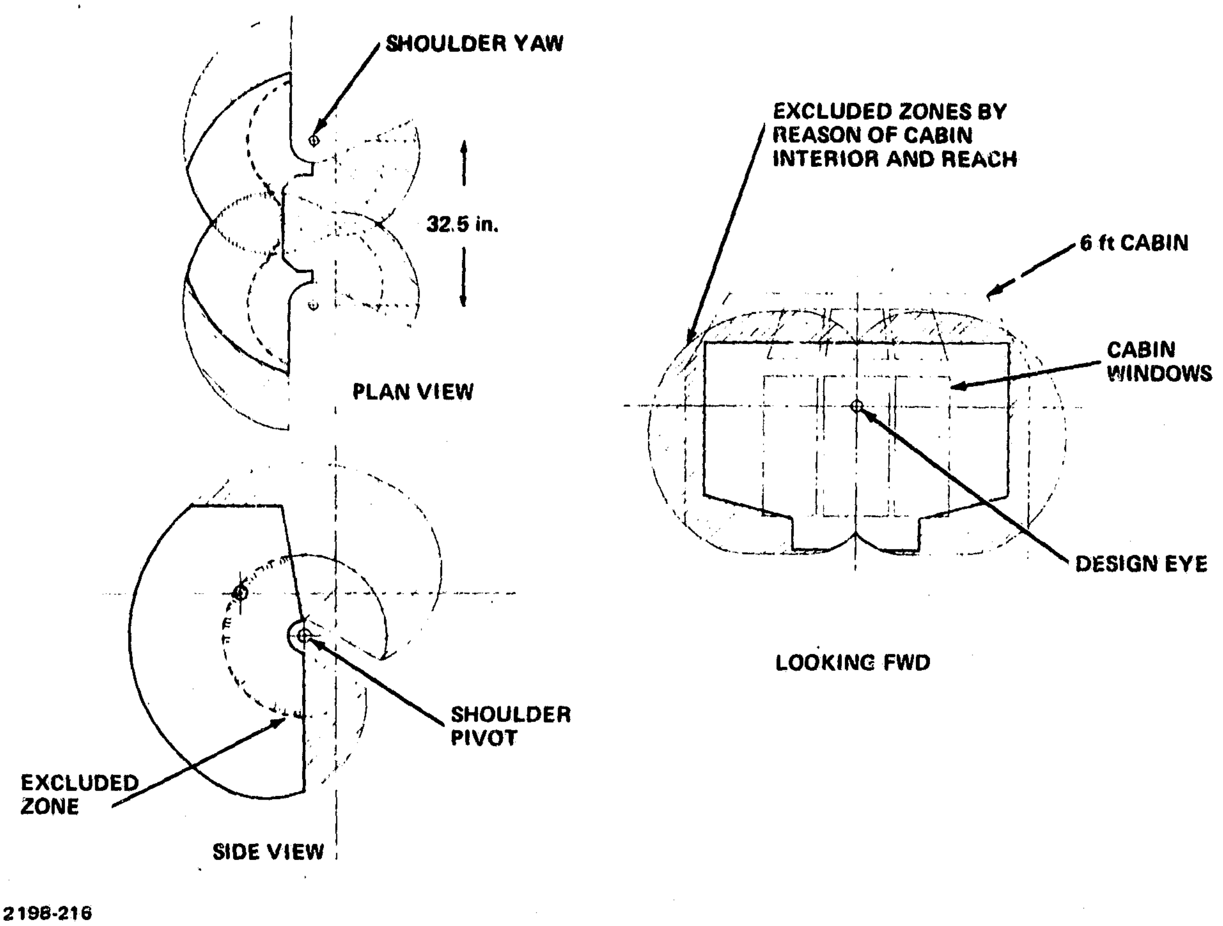

Figure 48. Master Control Volume

However, the arguments in favor of two dextrous arms are more compelling. Two identical dextrous arms are the familiar anthropomorphic arrangement. People are accustomed to working with two hands. Consequently, greater efficiency is anticipated with two handed activities. Having identical capabilities in left and right arms will improve operational flexibility near restricted access regions. When operations can be performed with a single hand, occasionally utilizing the opposite arm will reduce fatigue. The major components of projected large space structures are low-density, thin-walled "beams" with large aspect ratios (e.g., length/width = 40). Holding the beam with two dextrous arms separated by a meter or more permits control of beam position and attitude with relatively low force and torque inputs. The clearest case for two dextrous arms stems from tasks which seem to require two hands. These generally fall into the category of fastening or connecting. While one hand is holding and inserting a connecting member (e.g., a pit pin), the other hand is maintaining alignment of the bodies to be joined (or holding a tool, restraining a compliant member, etc.). Connecting a multipin electrical umbilical is another task which is normally done with two hands. With dedicated (and mechanically complex) end effectors, each of these tasks can be performed with one dextrous arm. However, the cost of developing a large number of dedicated end effectors is not warranted by the number of times these deivices are used. This is certainly true through the 1980's and may be true through the 1990's. For performing a large number of varied tasks (most of which are not defined today), a second dextrous arm seems the most cost effective solution. It is certainly the most flexible solution. The above arguments, for and against two dextrous arms, are summarized in Table 17.

2.3.4 Dexterous Manipulator Geometry and Size

To position a body at an arbitrary attitude and position, 6 DOF are required. However, to simulate the dexterity of a human arm, 7 DOF (in rotation) are required of a slave arm. Because this offers the most flexible tool that can be easily controlled, seven axes of rotation are selected for MRWS dextrous arms. Additional DOF in locating the shoulder position may be desirable. Variable shoulder separation (Y direction), height (Z), and extension (X) should be examined by simulation for their effects upon productivity. The recommended slave arm DOF and limits of motion are displayed on Figure 49. Wrist roll and yaw are both 360° motions for max versatility. Consequently, wrist pitch can be less than 90°. The 165° range shown

TABLE 17

NEED FOR TWO DEXTROUS ARMS – SUMMARY

PRO	CON
• FAMILIAR ANTHROPOMORPHIC ARRANGEMENT – HIGHER EFFICIENCY – MORE OPERATIONAL FLEXIBILITY • PERMITS ALTERNATE USE OF LEFT & RIGHT ARM FOR FATIGUE REDUCTION • MOMENT RESTRAINT ON EXTENDED STRUCTURES WITH LOW FORCE OR TORQUE INPUT • PERMITS FASTENING WHILE – RESTRAINING A SPRING – HOLDING A TOOL – PROVIDING ALIGNMENT	• SAME REACH ENVELOPE WITH ONE ARM • ADDED WEIGHT & COST OF ARM • ADDED WEIGHT & COST TO MRWS

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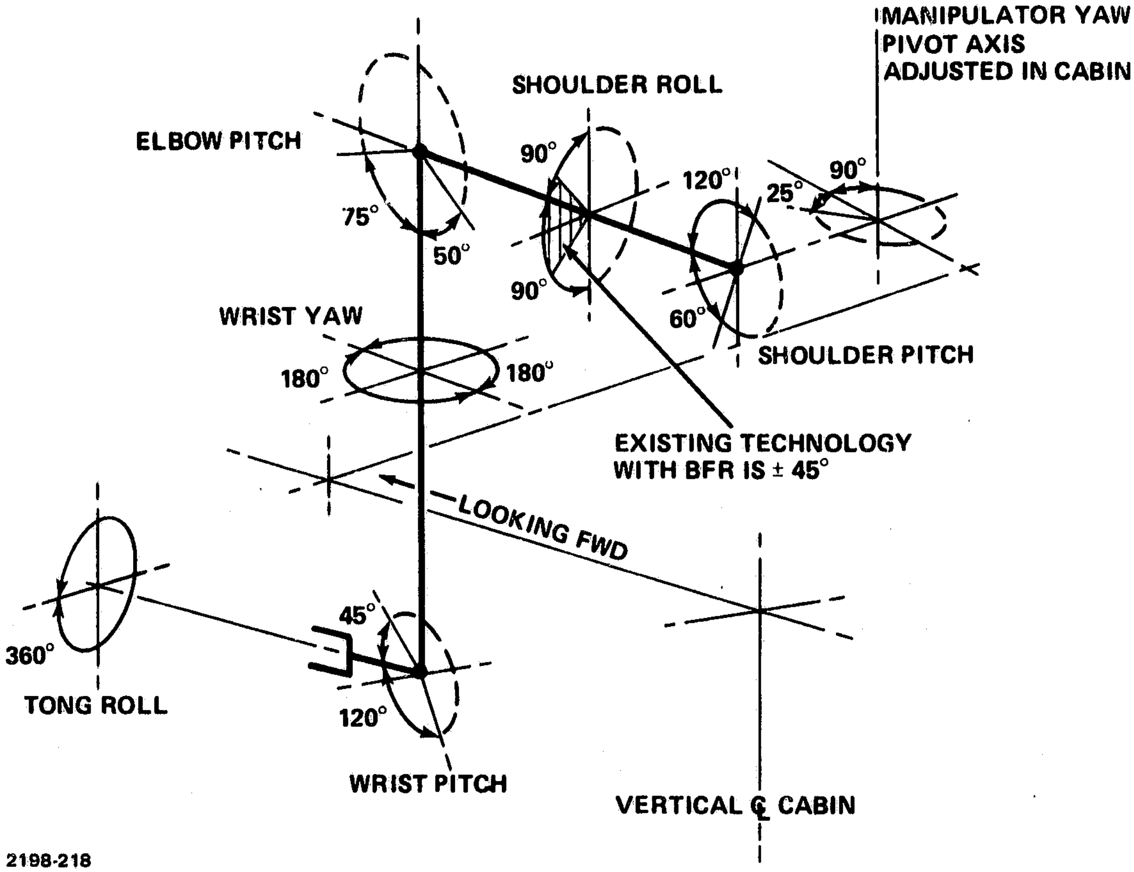

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Figure 49. Recommended Slave Arm Kinematics

is compatible with state-of-the-art (SOA) technology and enhances efficiency for some operations. Shoulder pitch of ± 90° is selected to provide the maximum working zone for the arm. By limiting elbow pitch to an angle less than 180°, an indeterminate arm position (a singularity) is avoided (the case when forearm and upper arm are approximately parallel). Elimination of this singularity eliminates control problems near that position, particularly when indexing and coordinate transformations are used. To provide a maximized working volume (see below), shoulder roll requirements are enlarged from the current SOA of ± 45° to the maximum available with bilateral force reflection (BFR). The goal is ± 180° in shoulder roll. The seventh DOF is shoulder yaw which is not a BFR motion. The 90° motion permits two dextrous arms to handle wide bodies. The 25° yaw motion is based upon the geometry of a particular MRWS installation.

Figure 50 displays some differences in working volumes between three identical slave arms which utilize differing amounts of shoulder roll. The left portion of the figure shows a top view of one half of the working volume generated by two dextrous arms with the motions described in Figure 49. The solid line defines the outside surface of a solid shape, a "mobility" region at the elevation of the shoulder. The mobility region is a portion of space which can be occupied by the wrist pitch pivot of the dextrous arm. The wrist can be any where within the mobility solid except the "excluded zone," the shaded parts of the figure. The excluded zone is a hollow within the mobility solid. It results from the inability of the slave forearm to be back against the slave upper arm (i.e., elbow pitch is -50° instead of -90°). As the shoulder roll angle is reduced from ± 180° to ± 90°, the exterior of the mobility solid is significantly reduced. It should be noted that the reduction takes place in a region which may be occupied by the grappler. Also, slight enlargement of the excluded zone occurs. When the shoulder roll angle changes from ± 90° to ± 45°, the exterior of the mobility solid is slightly reduced but the excluded zone grows substantially. Because the largest shoulder roll provides a significantly larger working volume, it is selected for MRWS flight vehicles.

Two views of a recommended work volume and slave arm placement relative to the MRWS cabin are shown on Figures 51 and 52. The side view (Figure 51) shows a preferred work zone which is a frustum of a 30° cone whose center is the design eye.

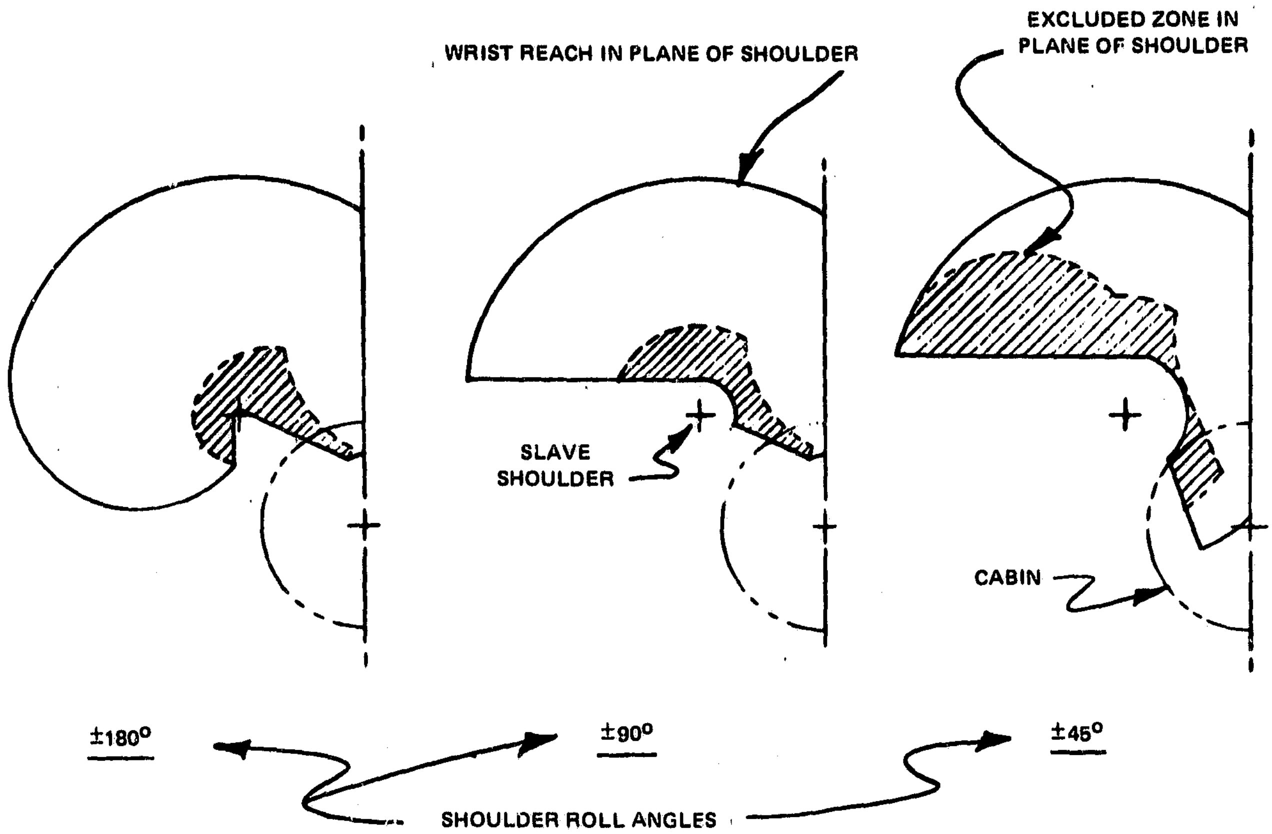

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Figure 50. Influence of Shoulder Roll on Work Volume

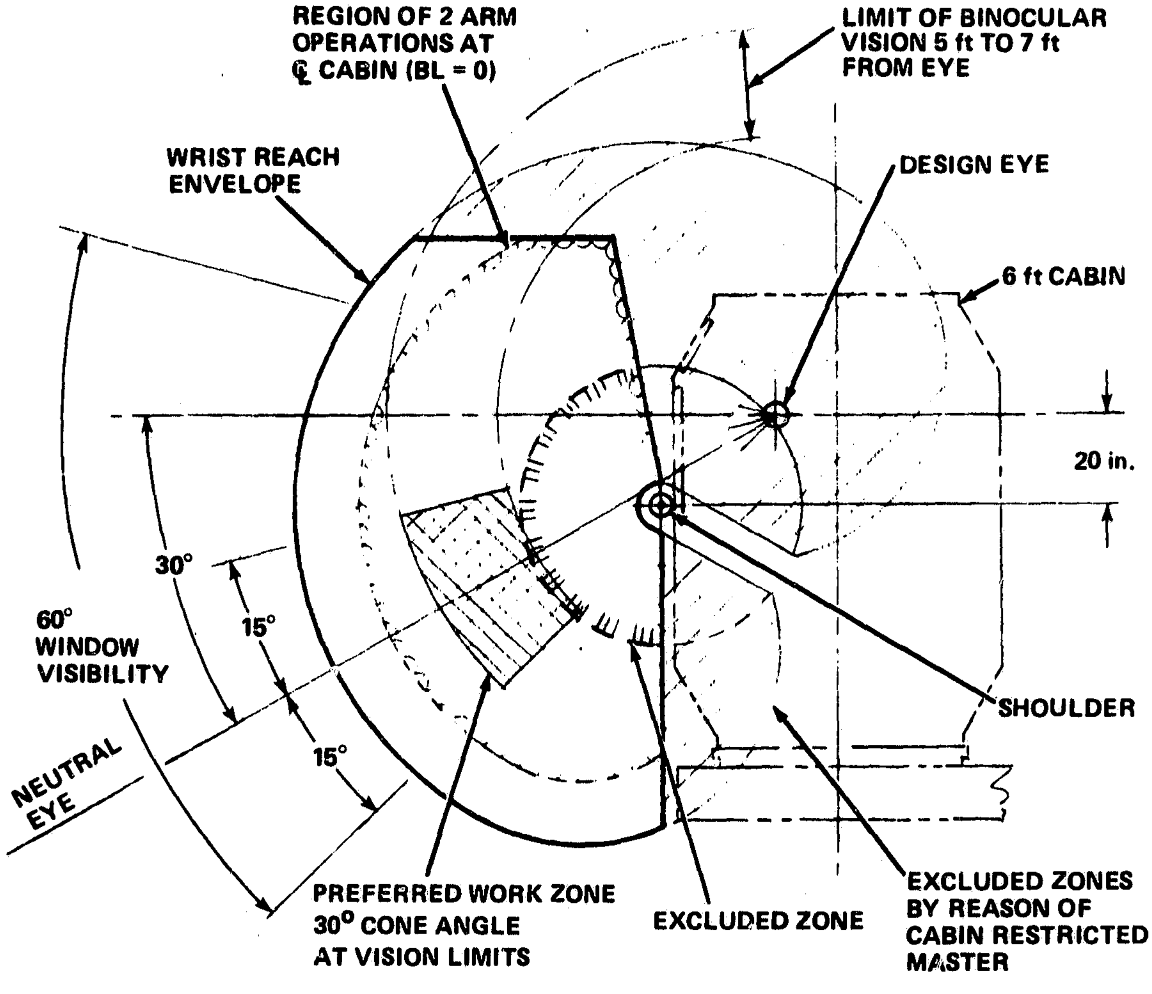

Figure 51. Slave Work Volume – Side View

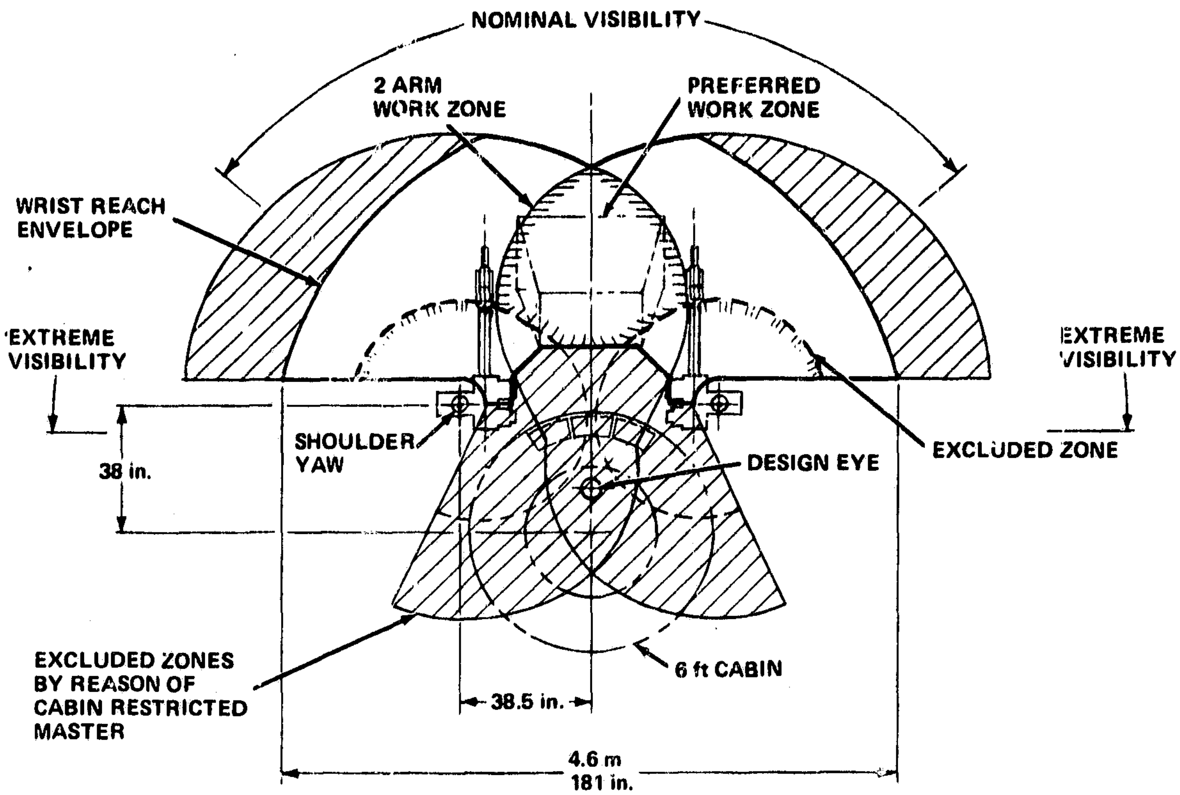

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Figure 52. Slave Work Volume – Top View

The 30° value is based upon aircraft cockpit studies. The preferred work zone is located in the lower visability region because prior work done with manipulators (Reference 1)* indicate that the preferred visability angle is approximately 45° below a horizontal. The outer edge of the zone is 7 ft from the operator's eye, the approximate limit for binocular vision when handling small objects (less than 1 in.). The inner edge of the preferred work zone is 5 ft from the operator's eye and is just outside of the exclusion zones. The intersection of the two mobility solids (from left and right dextrous arms) at the cabin's center plane is shown as a kidney shaped figure with shaded boundary lines in Figure 51. This is the region where both slave wrists can be in close proximity. Consequently, it approximately defines the region for close two arm cooperative tasks. As the preferred work zone is moved upward toward the horizontal, part of it leaves the kidney shaped two arm region. However, two-arm cooperative work is still possible in the upper regions of the figure because the end effectors extend beyond the wrists (which defined the region). The relative position of two-arm cooperative work region and preferred work zone is established by the location of the slave shoulder relative to the operator's eye. The 30-in. height was selected to keep the shoulder (and, presumably, most of the slave arm) below the lower edge of the window to minimize visual obstructions. Consequently, a 2-m arm is required to permit two arm cooperative work in the 7 ft limit in the upper region.

The top view (Figure 52) shows each dextrous arm shoulder placed ± 43 in. off the cabin centerline. This was done to keep the shoulder pivot support structure out of the normal range of vision. Additionally, it keeps the exclusion zones away from the windows and permits holding wider objects. However, when the operator moves his eye closer to the window, he is able to see the pivot and slightly behind it. The two arm work zone shown in Figure 52 (the region common to both mobility solids but outside the exclusion zones) is drawn in the plane of the shoulders. A cross section through the two arm work zone at eye level would show a region which included all of the windows. Consequently, two handed work can be performed directly in front of the windows and almost to the limit of reach of the two dextrous arms. The preferred work zone has been shown as a portion of a pyramid in Figure 52. It lies entirely within the two handed work region.

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*References may be found at the end of Section 2.

The maximum operating force at the tip of a dextrous arm is 67 Newtons (15 lb). This force is required to connect a fluid coupling (Reference 2). The maximum tip speed of the slave will be determined by considerations of productivity (high speed) and safety (low speed). An upper limit of 0.75 m/sec (30 in./sec) is based upon the observation limits of a human eye. Higher velocities are not perceived accurately.

Because hydraulic systems are undesireable for space applications, electromechanical power generation is required for dextrous arms. Power transmission options are shown on Figure 53. Two manipulator experts have recommended the hybrid approach as the best technique for meeting MRWS objectives.

A replica master slave arrangement is recommended (Figure 54) which implies similarity of geometry and orientation between master and slave. However, two differences are planned. Reduce operator fatigue by using a pistol grip for the master handle instead of the single DOF CRL tong. The other difference is in control of slave yaw motion. To position a body at an arbitrary attitude and position, 6 DOF are required. Conversely, the position of the control handle will uniquely determine the position of a 6 DOF master. However, to simulate the dexterity of a human arm, 7 DOF (in rotation) are required of a slave arm. Either the master must operate with 7 DOF and the resulting position indeterminancy, or 1 DOF must be removed from the master and placed on a separate control dial or switch, or an additional constraint be made between operator and master (e.g., a forearm "sleeve"). Based upon unsatisfactory experiments with controllers with more than 6 DOF and a desire to leave the operator unencumbered, it is recommended that shoulder yaw be made independent from the master.

2.3.5 Dexterous Manipulator Control Modes

2.3.5.1 Productivity Evaluation - The approximate relative efficiency between three control modes is shown in Figure 55. Bilateral force reflection (BFR) is the most efficient and is used as the standard for time comparisons. NFR Replica is a position control device which uses master/slave control with a 1:1 ratio. It is nonforce-reflecting and relies only on visual cues for operator feedback. Resolved motion rate control (RMRC) utilizes a 6 DOF hand controller(s) to establish the direction of motion and tip speed of a slave arm.

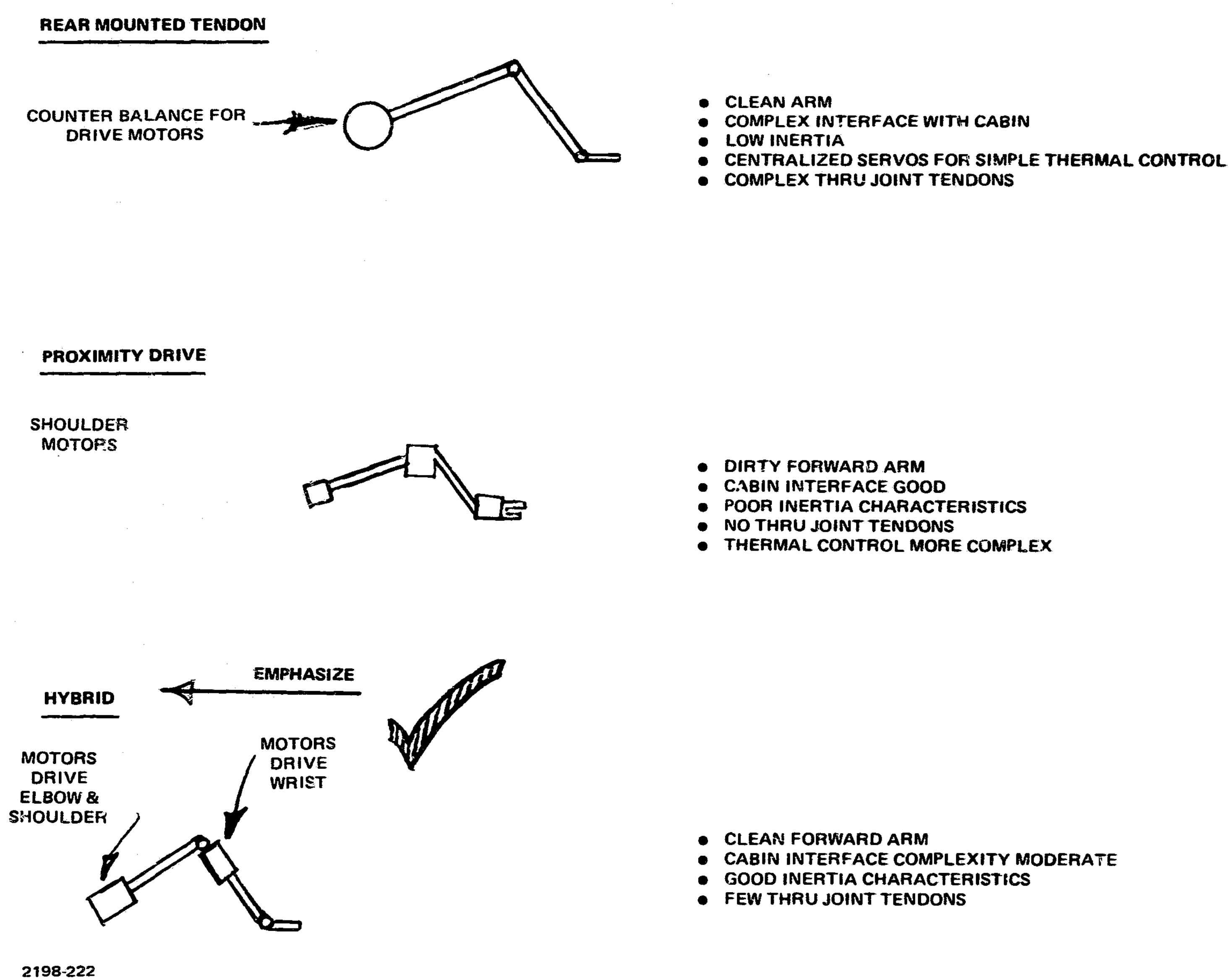


Figure 53. Drive System Options

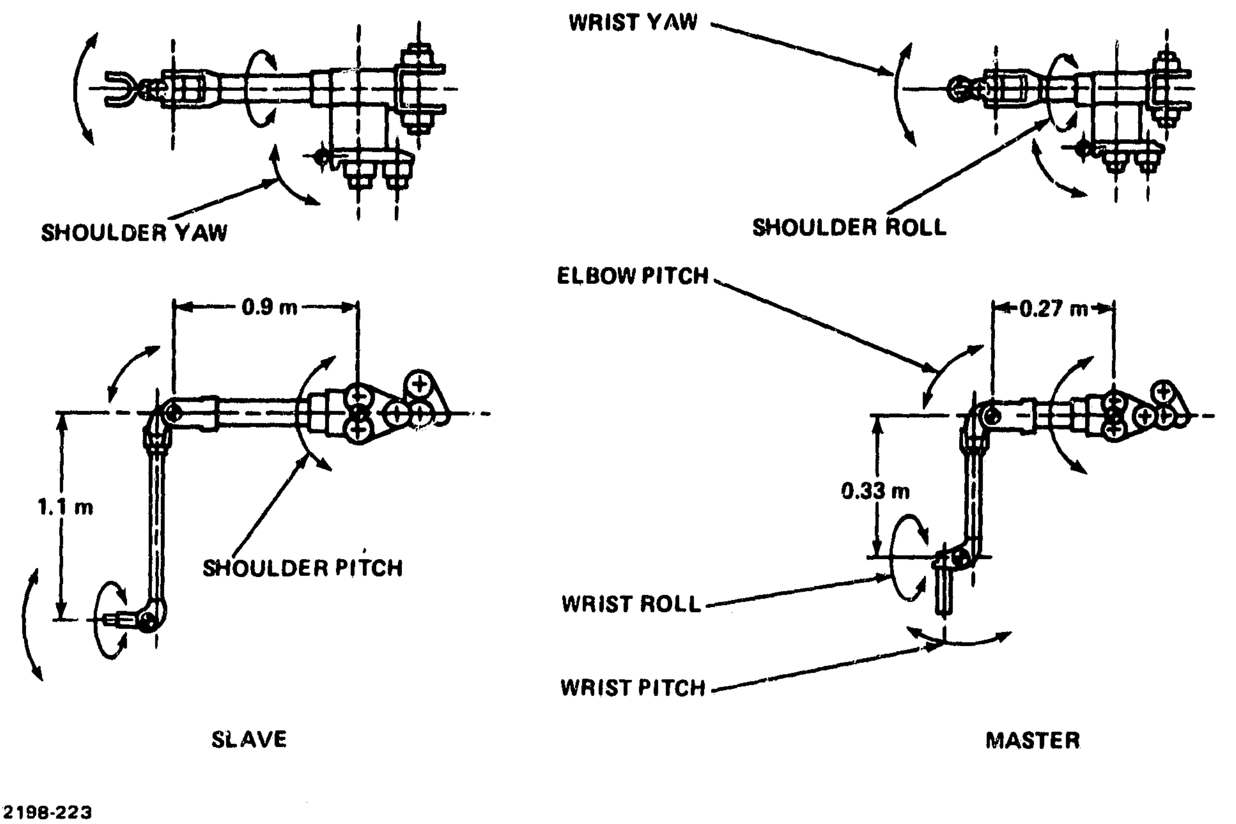
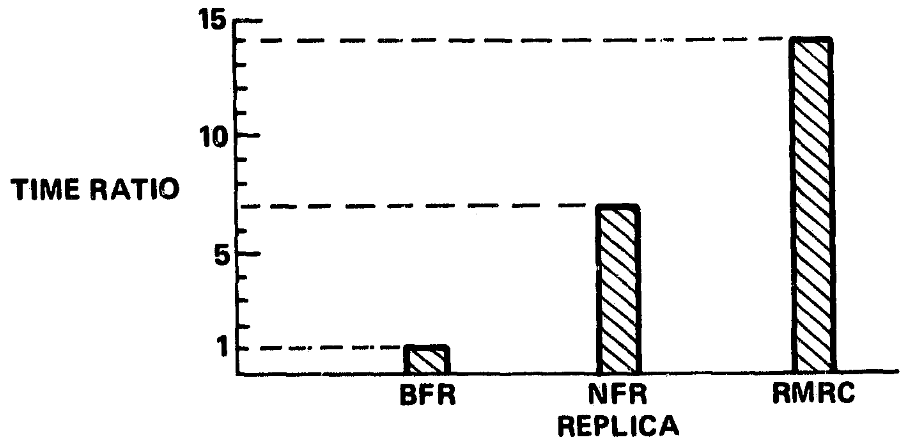


Figure 54. Dexterous Manipulator Arrangement



VERTUT ET AL, "CONTRIBUTIONS TO DEFINE A DEXTERITY FACTOR FOR MANIPULATOR," PROC. OF 21ST CONFERENCE ON REMOTE SYSTEMS TECHNOLOGY 1973

NEVIS ET AL, "THE MULTIMODED REMOTE MANIPULATOR SYSTEM," FIRST CONFERENCE ON REMOTELY MANNED SYSTEMS, 1972

FLATAU, "TASK TIME COMPARISON OF THREE MANIPULATOR CONTROL MODES, BFR, UNILATERAL AND RATE CONTROLLED," 1969 AND 1978, UNPUBLISHED

FLATAU ET AL, "SOME PRELIMINARY CORRELATION BETWEEN CONTROL MODES OF MANIPULATOR SYSTEMS AND THEIR PERFORMANCE INDICES," FIRST CONFERENCE ON REMOTELY MANNED SYSTEMS, 1977

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Figure 55. Summary Relative Task Times and Supporting Evidence for Productivity Decision

The tests which form the basis for the displayed data were not optimized for either space tasks or the comparison that is presented here. On some, dissimilar manipulators were used for comparing task times. On others, an insufficient number of tests were conducted; none of the test sequences were related to space construction.

However, all known tests results indicate a significant advantage in task efficiency for BFR. Its nearest competitor, NFR, requires about seven times more time for average tasks. Because productivity is a compelling parameter for fabrication of future very large space structures, it is recommended that BFR be evaluated in an MRWS simulation laboratory.

2.3.5.2 BFR versus Non-BFR: Test Results of 3-12-78

Table 18 data was obtained by Carl Flatau in his laboratory. Because available time was limited, each task was performed only four times. Consequently, a large quantity of data scatter is evident. The general conclusion is that BFR was 6.7 times more efficient than NFR Replica for these tasks.

2.3.6 Indexing of Manipulators

Indexing is a technique which permits a change in the relative positions of master controller and slave dextrous arm. It is used to permit operation of a master within a restricted volume at motion ratios which would prevent the slave arm from covering its full working volume. The need for indexing is established by the high recurring cost of a flight vehicle cabin (currently estimated at $2.9M/ft of cabin diameter). If indexing can permit a much smaller cabin diameter without a significant loss of productivity, it will be cost effective.

With an indexing system, there will be times when the angular orientation of the slave hand will be significantly different from that of the master. An angular mismatch of up to 30° can be tolerated by an operator. Beyond 30°, it is very difficult (i.e., inefficient) to perform work because slave motion is in a significantly different direction from master motion. Consequently, a coordinate transformation system is required which converts force and velocity inputs at the master hand into vehicle coordinates (x, y, z, ϕ, θ, ψ). The slave hand is commanded to move to the desired position by transforming the vehicle coordinates into the slave coordinate system. These transformations enable the operator to maintain a constant visual

TABLE 18

BFR VERSUS NON-BFR: TEST RESULTS OF 3-12-78

TASK	TEST RESULTS IN SECONDS				TASK TIME RATIO: NFR/BFR
	BFR		NFR		
	MEAN* TIME	STD DEV	MEAN* TIME	STD DEV	
1. REMOVE PIN (3/8 in. dia. 0.0005 in. FIT)	4.0	0.6	31.0	8.9	7.8
2. PUT PIN DOWN	1.2	0.9	4.75	1.5	4.0
3. PICK UP PIN (VISION OBSTRUCTED)	1.5	1.0	26.2	15.6	17.5
4. REINSERT PIN	8.0	0.9	48.0	6.1	6.0
5. PICK UP T HANDLE ALLAN WRENCH	1.8	1.0	19.8	1.6	11.0
6. INSERT IN SCREW (VISION OBST)	3.4	1.6	50.2	12.8	8.0
7. TURN WRENCH 3½ REV	9.0	0.5	56.3	11.3	6.3
8. RETURN WRENCH	3.0	0.7	26.5	6.7	8.8
9. GRAB AIR IMPACT WRENCH	1.3	0.8	9.3	8.7	7.2
10. PLACE ON BOLT	1.5	0.5	6.8	5.3	4.5
11. SCREW DOWN	1.0	0.2	7.3	11.5	7.3
12. REMOVE	1.0	0.3	3.5	5.6	3.5

AVERAGE RATIO = 6.75; STD DEVIATION OF RATIO = 2.2

*TESTS USED 2 OPERATORS; EACH OPERATOR PERFORMED EACH TASK 2 TIMES

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reference frame. Plus x motion of the master always produces +x motion at the slave hand. Even if indexing is not used, coordinate transformations will be required when the slave arms are rotated about the yaw axis by a dial controller.

Several types of indexing are possible. For all types, a general goal is to maintain a tip speed ration of 1"1 between slave and master while doing a dextrous task at a worksite. Zone type indexing always maintains a 1"1 ratio. When the limits of master motion are reached in any direction, the master is uncoupled from the slave and moved by the operator to the opposite end of the control volume. When the master is re-connected to the slave, indexing is completed. Indexing can be either automatic or by operator control (e.g., a button on the control handle). A second type of indexing has been termed Dual Ratio. This utilizes a very large slave/master angular position ratio to permit full slave travel with the restrictions of small master working volume. The high ratio is used to transport the arms (and tools, etc.) to the vicinity of a worksite. Once there, indexing is performed. This moves the master to the center of its control volume while the slave position is locked. After the master is centered, the slave is unlocked and a 1"1 tip motion ratio is maintained. A third type of indexing is similar to the Dual Ratio system. However, instead of using a high ratio position controller with resisting forces at the master, it used a resolved motion rate control for large excursion transport operation. This technique is called a Rate-Position system. For dextrous activities at a worksite, a 1:1 position control with BFR is used. These, and other promising indexing concepts, should be evaluated by simulation with task productivity used as the selection criteria.

2.3.7 Stabilizer-Single-Point versus Three-Point Pickup

The principal advantage of three grapples attaching an MRWS to a worksite is a higher level of allowable torque input to a worksite. This characteristic is the result of the type of large area, low mass, open structure that will be used for future space programs. The elements of these future structures can carry relatively high axial loads, but their capabilities for moments and transverse loads are severely limited. Consequently, large moments can be delivered to these structures by applying equal and opposite axial loads separated by a distance of several meters. This can be achieved by a three-grapple system after a berthing operation is completed. During berthing, torques applied to a worksite are approximately the same for the three- or one-grapple system.

To accept the loads required for certain tasks, grappling lugs may be required at all worksites. These lugs would add cost and weight for the sole purpose of permitting MRWS operation without damaging a worksite. If these lugs are required, a three-grapple system imposes a severe penalty on a construction base. In addition to requiring three lugs for every lug of a one grapple system, additional lugs are required to permit a three-grapple MRWS to change attitude/position to perform another task at the same worksite. Consequently, the potential impact of a three grappler MRWS on a large construction base or large structure is highly unfavorable.

A strong case for a single-grapple system can be made independently of the issue of grappling lugs. The argument is summarized in Table 19. For comparable degrees of freedom, a single grapple will weigh and cost less than a three-grapple system. Because a three-grapple MRWS will require an additional bearing at the upper-grapple structure/cabin interface (to permit cabin rotation), MRWS cost and weight will be higher. The strongest argument in favor of a single-grapple system is enhanced productivity. More time is available for dextrous arm tasks because less time is consumed in berthing and MRWS attitude and position changes. After berthing, a single-grapple system has access to more than four times the working volume of a three-grapple system. This is shown in Figure 56. The manipulator reach envelopes represent the limits of a particular MRWS design manipulator length and dexterity, combined with the available MRWS cabin motion. The more restricted envelope results from the three grapplers fixing the location of the cabin. Consequently, only the 360° cabin rotation is available to enlarge the manipulators working volume. With a single grapple, the cabin can be yawed from side to side and rolled 180° to a substantially larger working volume. This permits several nearby tasks to be performed with one berthing operation. It also makes task location relative to worksite-berthing-point location far less critical.

2.3.8 Stabilizer Design Conditions

The primary function of the stabilizer is to hold the MRWS to the worksite as opposed to holding any particular piece of hardware to the MRWS. Because the cherry picker is generally too compliant to do this job effectively, the MRWS mass, inertia, and torques applied by the dexterous manipulators are maximum load inputs to the stabilizer. A single-stabilizer approach has been selected instead of multiple pickups because of the operational flexibility afforded by a single worksite interface.

TABLE 19

SINGLE VERSUS THREE-STABILIZER SYSTEM

SINGLE STABILIZER	THREE STABILIZERS
• LOWER STABILIZER COST • LOWER STABILIZER WEIGHT • LOWER MRWS COST AND WEIGHT • HIGHER PRODUCTIVITY: – REDUCED BERTHING TIME – LARGER WORKING VOLUME – BETTER WORKSITE ACCESS	• HIGHEST TORQUE INPUT TO WORKSITE

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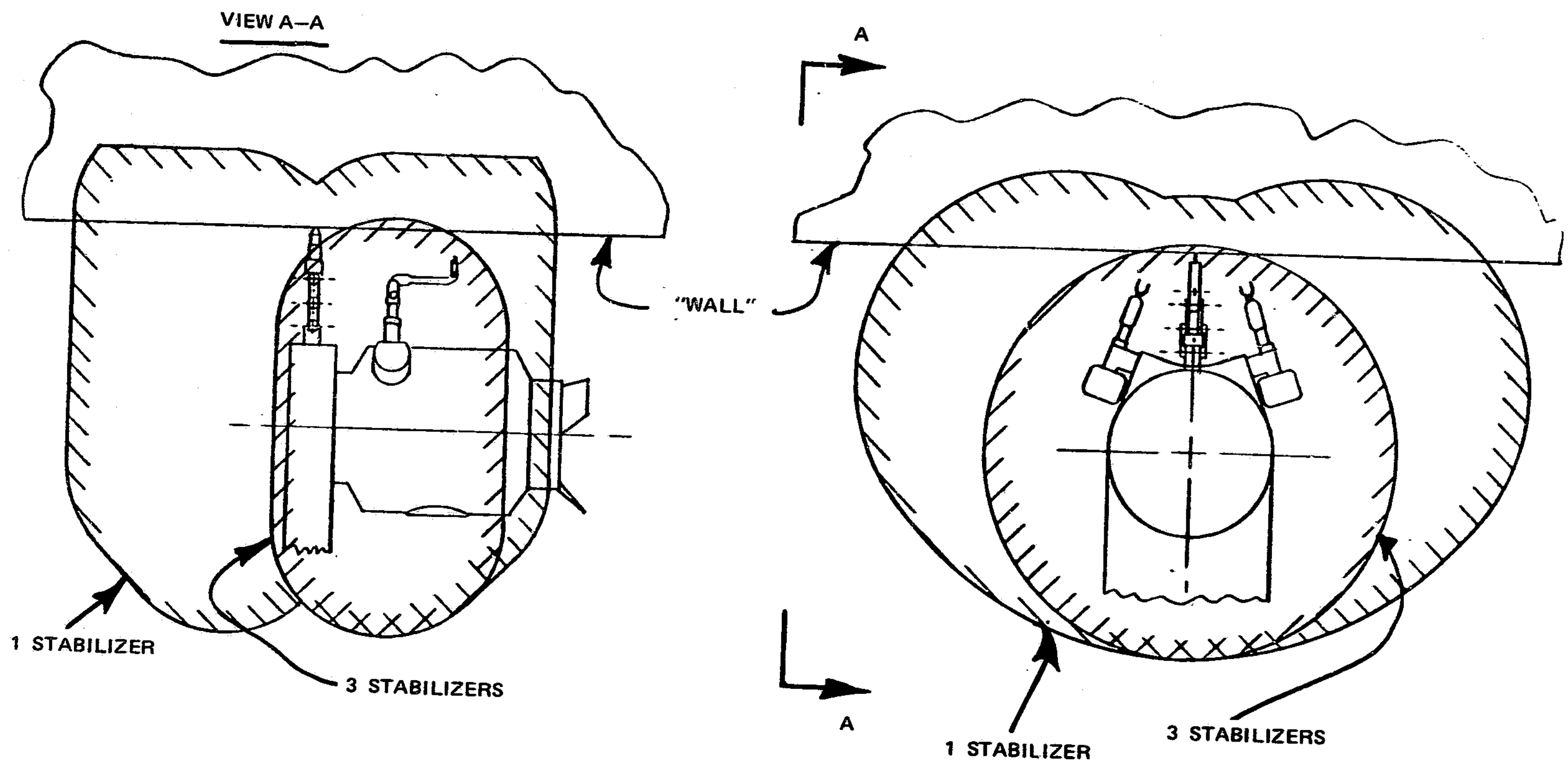

- CONCLUSION
  1 STABILIZER ALLOWS >4X WORKING VOLUME OF 3 STABILIZERS

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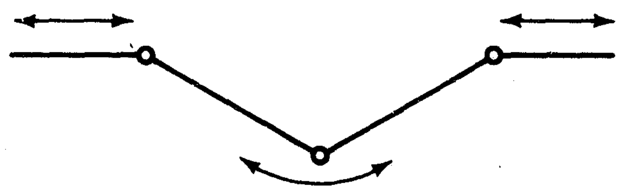
Figure 56. Single Stabilizer versus Three Stabilizers: Working Volume

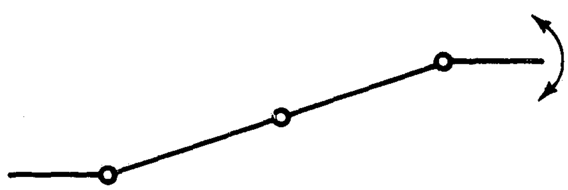
The stabilizer also fine positions the MRWS with respect to the worksite. The desired motions for this function are as follows:

1. Approach and Recede
2. Up and Down
3. Pitch Adjustment
4. Yaw Adjustment
5. Roll Adjustment
6. Angular Conformance of the End Effector to the Worksite

Because Item 4 is accomplished by the MRWS rotary bearing, Item 3 and 4 need not be done simultaneously by the stabilizer. Items 1 and 2 are achieved by simultaneous shoulder, elbow, and wrist pitch motions, i.e.



Item 3 uses the same degrees of freedom as follows:



Item 5 is accomplished with a shoulder roll. Requirement 4 is met by pitch motions with 90° of shoulder roll. Item 6 is provided by wrist pitch with wrist yaw and roll added.

The required motions are thus provided by the rotary bearing and the following 6° of freedom with the stabilizer:

- Shoulder roll and pitch
- Elbow pitch
- Wrist pitch, yaw, and roll.

The stabilizer torque requirement is based on the desired acceleration to 0.05 rad/sec in 2 sec or 0.025 rad/sec^2. For a 7000-lb MRWS with the stabilizer interface 70 in. from the center of gravity, the dynamic torque capability required is approximately 3000 in.-lb. A typical stabilizer joint has a static capability equal to three times the dynamic torque, or about 9000 in.-lb. These values are very close to those available with commercial power manipulators.

The selected value for tip speed is dependent on the control mode; for rate control, 1 rad/sec no load speed is adequate.

Required arm lengths are very dependent on worksite geometry. Minimum upper and lower arm lengths of 24 in. are considered adequate values for stabilizer design purposes.

2.3.9 Berthing Design Requirements

To enable an MRWS to transfer personnel with an orbiter, a low-energy dissipating berthing system shall be used. The berthing device, a system of three latches outside of the MRWS hatch, engages a similar device on the orbiter airlock module. Berthing engagement speed and position are controlled by the MRWS operator driving the cherry picker arms. The cherry picker arms go slack after berthing is completed.

Berthing an MRWS to a worksite utilizes a single stabilizer arm. A special end effector is required for each type of berthing attachment. For example, a berthing lug composed of a 1-in. diameter by 12-in. long rod may require a hand type end effector which squeezes the rod. Or, for berthing to a one meter beam without lugs, an end effector which clamps to the intersection of vertical and diagonal stiffeners can be used. Actual values of berthing velocities and engagement angles must wait for design definition of a cherry picker arm and the berthed structure. For current analyses, the following range of values may be assumed for berthing velocities: 1 cm/sec $\leq$ V berth $\leq$ 25 cm/sec. To dissipate berthing energy (and prevent failure of worksite structure), the grappler brakes are used in a "Berth Mode." This mode permits a controlled increase in brake torque, from zero at pre-engagement to maximum value at completion of berthing (TBD seconds later).

2.4 ENVIRONMENTAL CONTROL AND LIFE SUPPORT

2.4.1 Shirtsleeve versus Pressure Suit

2.4.1.1 Evaluation - Because the proposed MRWS requires high crew activity levels, maximum mobility and comfort are essential design requirements. The shirtsleeve environment is a clear choice for this application.

A second consideration involves the necessity of prebreathing (3 hr) pure oxygen prior to crew use of current design pressure suits (due to nitrogen contained in Orbiter atmosphere). Pre-breathing could be eliminated if a nitrogen/oxygen atmosphere of 8 psia suit is used in the suit but crew mobility would be problematical.

The technology (including hardware) for providing a shirtsleeve environment is available.

2.4.1.2 Recommendations - It is recommended that a shirtsleeve environment should be provided in the closed cabin MRWS.

2.4.2 Cabin Pumpdown versus Blowdown

For MRWS applications where it is attached to a space construction base and cabin depressurizations are scheduled frequently, a drade study shows that cabin pumpdown is advantageous on the basis that the reclaimed atmosphere is pumped into an adjacent compartment with a large volume (2500 ft^3) and a similar environment to the MRWS (Figure 57).

A pumpdown time of 15 min to 2.0 psia results in a compressor peak power requirement of 3 kW. (A minimum pumpdown pressure of 2.0 psia is selected to be reasonable for a single stage compression ratio to 14.7 psia).

For emergency/rescue operation, cabin blowdown should be employed to minimize operational time. Also, for applications where cabin pressure reduction is infrequent, there is no need to incorporate a pumpdown system.

2.4.3 L_i OH_2 versus Amine Air Purification

A regenerable solid amine system, which is currently under development for the Shuttle, was selected for CO_2 removal as the best of several candidates. As seen in Figure 58, Li OH is smaller and lighter for relatively short periods. However, the mission weight/volume penalties of multiple expendable cartridges are unacceptable for the high-use MRWS. The other systems require GSE, service supplies and/or

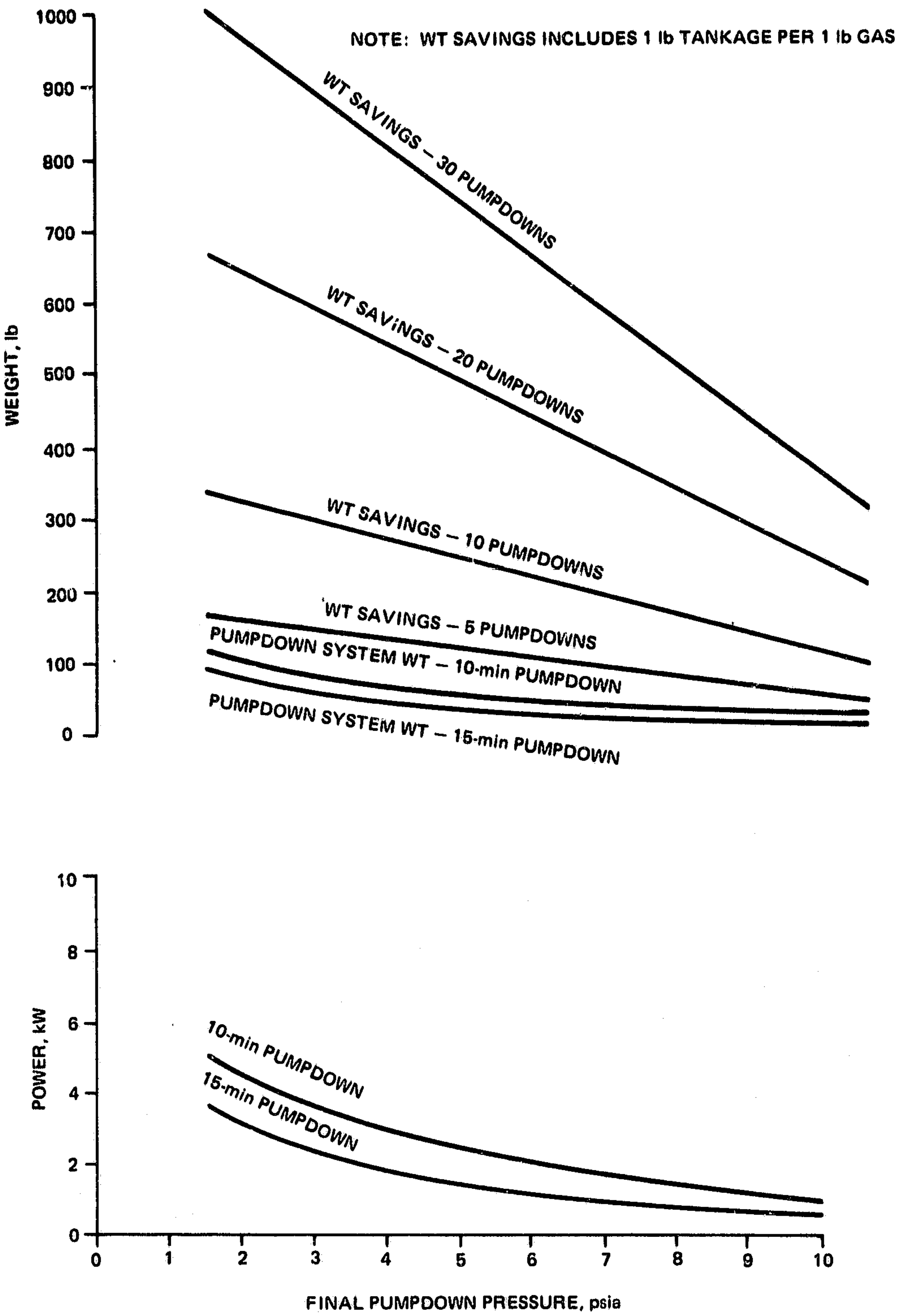


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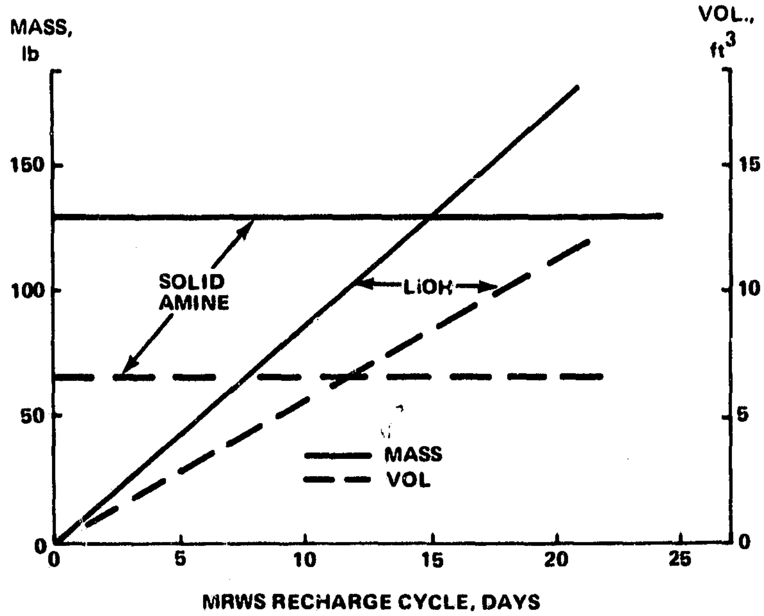
Figure 57. MRWS Pumpdown versus Blowdown



- HUMIDITY CONTROL MAINTAINED VIA SOLID AMINE BED; PERMITS INCREASED INLET COOLANT TEMPERATURE; RESULTS IN 10% REDUCTION IN RADIATOR AREA (85 ft^2 VS 95 ft^2)

AFT EQUIPMENT BAY

- ELECTRICAL LOAD 228 W
- PASSIVE HEAT REJECTION @ AVG RADIATOR TEMP 155° F
- REQUIRED RADIATOR AREA 5.2 ft^2
- AVAILABLE AREA (AFT EQUIPMENT BAY REAR SURFACE) 6.3 ft^2

(HAMILTON STANDARD TRADE STUDY)

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Figure 58. Comparison of LiOH versus Solid Amine ECLS

bake-out routines, all of which are unneccessary with the solid amine system. The selected system also provides inherent humidity control which permits an elevated inlet coolant temperature, thereby minimizing required radiation area.

A simple, single fluid (FC-40) thermal transport system was selected since the coolant circuits within the cabin are small, and damage potential is low.

To conserve space and reduce cabin heat loads, all equipment which need not exist in the pressurized volume is mounted in an aft equipment bay. Because sufficient radiator surface is available to passively cool this equipment, no additional coolant loops are required in this area.

2.4.4 Sublimator versus Radiator

Rejection of the heat load from the MRWS cabin requires a radiator because use of consumables (4.5 to 5.0 lb/hr of water in a boiler or sublimator) is impractical. Current radiator design indicates a required surface area of 80 - 90 ft^2, depending on MRWS window area.

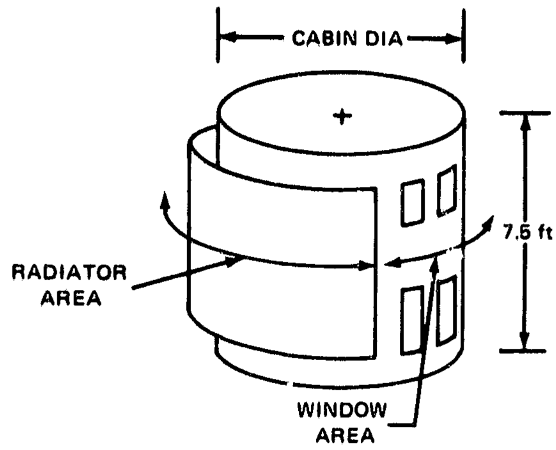
Because window area and integral radiator area are proportional to cabin diameter for a fixed cabin height, a trade study was made to show minimum cabin diameter (Figure 59) is 6 ft.

2.4.5 ECLS Design Conditions

The basic design requirements for the environmental control/life support subsystem are listed in Table 20. These assume the equivalent of continuous one man operation for seven days in a closed cabin pressurized to one atmosphere. ECLS requirements are essentially the same for all versions of the closed cabin MRWS. Open cherry picker operations require the standard pressure suit as with any EVA.

To minimize storage volume, consumables are stored in 3300 psi composite tanks similar to those used on the shuttle. Total storage volume for the O_2, N_2 and emergency O_2 tanks is 6.4 ft^3.

The ECLS radiator is sized to reject 1447 watts of interior cabin heat resulting from metabolic, subsystem, and external sources.



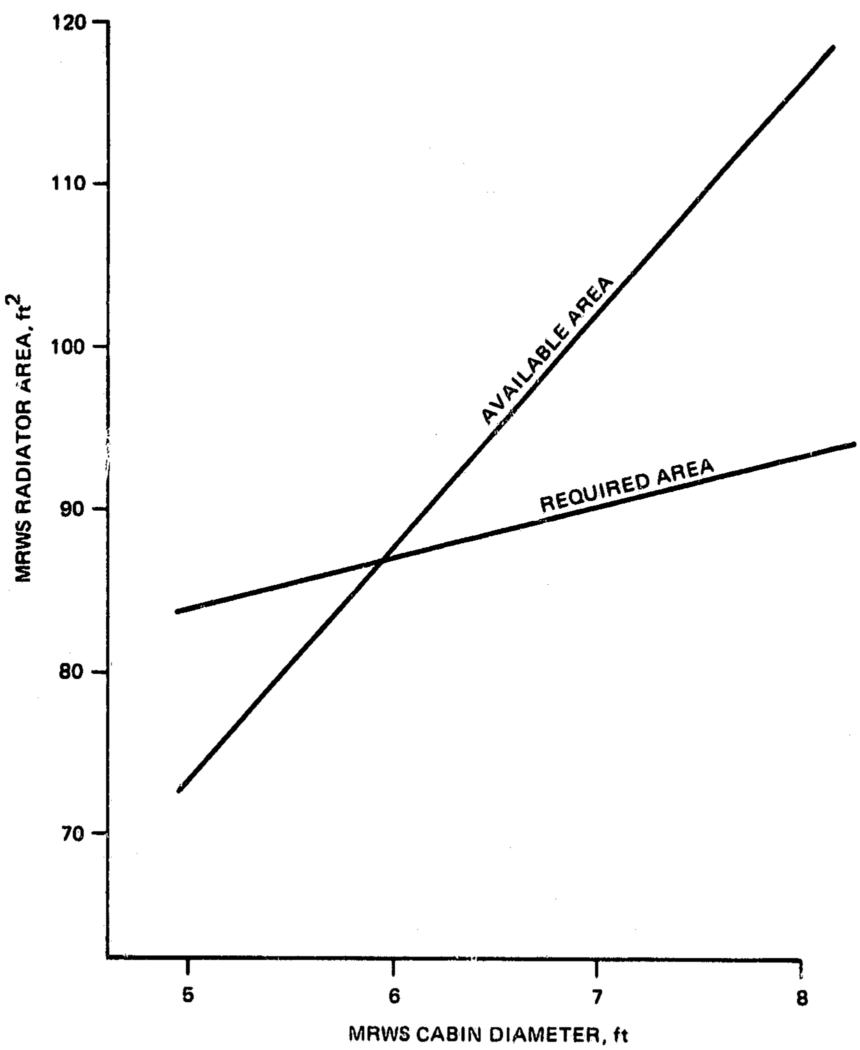


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Figure 59. MRWS Cabin Diameter versus Radiator Area

TABLE 20

SUBSYSTEM REQUIREMENTS – ENVIRONMENTAL CONTROL/LIFE SUPPORT (ECLS)

OCP	CCP	CRANE	FREE FLYER
STANDARD EVA REQMTS	← PRESSURIZED CABIN →		
	• PRESSURIZED FREE VOLUME	168 ft^3	
	• AIR (O_2/N_2)	14.7 psia	
	• TEMPERATURE	75 – 85° F	
	• HUMIDITY (DEW PT)	45 – 60° F	
	• RECHARGE	7 DAYS	
	• METABOLIC (3 – 8 hr SHIFTS, 1-MAN CONTINUOUS)		
	– AVG LOAD	1200 BTU/hr	
	– PEAK LOAD	1600 BTU/hr	
	– CO_2 GENERATION	5.0 lb/DAY	
	– H_2O GENERATION	14-20 lb/DAY	
	• CONSUMABLES	OXYGEN	NITROGEN
	– LEAKAGE (lb/DAY)	0.4	1.6
	– METABOLIC (lb/DAY)	4.2	–
	– 2 REPRESS (lb)	7.5	30.0
	TOTAL (lb)	39.7	41.2
	– 3300 psi TANK (in.)	20	–
	– EMERGENCY O_2 (lb)	20	–
	TANK (in.)	15.5	–
	• CABIN INTERIOR HEAT LOAD		
	– METABOLIC (1200 BTU/hr)	350 W	
	– CO_2 REMOVAL	50	
	– ELECTRICAL	822	
	– SOLAR INPUT (WINDOWS)	255	
	TOTAL	1447 W	

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2.5 CONTROLS AND DISPLAYS

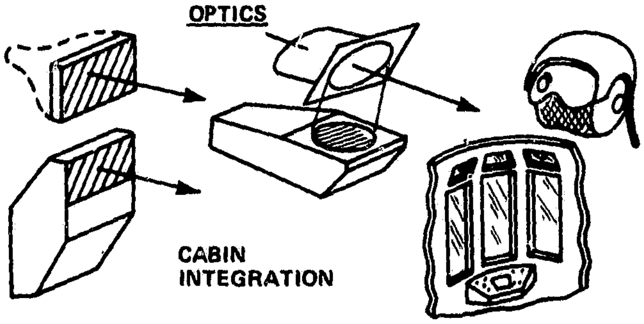
2.5.1 Display Technology Options

2.5.1.1 Display Alternatives - The integration of different display functions in a single element was investigated as an area which can greatly reduce total C&D volume and power. Display technology options were assessed (Figure 60) to establish a baseline approach which best meets the MRWS requirements including moderate advances in state-of-the-art display capabilities. Displays are divided into two parts: the display device which generates the image and the display optics that transport the image to the observer's eye.

The device is generally either electron beam addressed or matrix addressed. The former uses a moving electron beam to generate the image while the latter uses coincident current techniques similar to computer core addressing methods. The CRT and the first four matrix addressed panels were selected for further evaluation. A comparison of the two devices indicates power and reliability advantages with the matrix panels but more versatility in display capability with the CRT.

The display optics either require viewing of a display surface (direct, ported and projected optics) or use optical techniques to superimpose the information on the scene viewed by the person. Direct, ported and helmet-mounted optics were selected as candidates for use in the MRWS. Heads-up approaches were ruled out because the window arrangement and work region geometry of the MRWS is considered unsuitable when viewing is not restricted to a particular direction.

DEVICE COMPARISON	
MATRIX ADDRESSED FLAT PANEL	CATHODE RAY TUBE
LOW POWER	MULTICOLOR AVAILABLE
LOW VOLTAGE	MORE GREY SHADES
LESS VOLUME -- DEPTH	HIGHER RESOLUTION
HIGHER RELIABILITY	LOWER COST (?)
LONGER LIFE	NO ERASING MODE
SOFT FAILURE	WIDE SELECTION OF
INHERENT MEMORY	FORMAT SIZES
UNIFORM RESOLUTION	MATURE TECHNOLOGY
INSTANT ON/OFF	ADDRESSING EASY
LOW DISTORTION	



CCP APPROACH

- MINIMIZE CABIN VOLUME, PANEL DEPTH, PWR
- VISIBILITY – WINDOWS, STATUS, C&W, CCTV
- CONVENIENCE – CONTROLLERS
- COMBINATION OF LUNAR MODULE PLUS INTEGRATED PANELS

DEVICE TECHNOLOGY

- ELECTRON BEAM ADDRESSED
  - CRT
  - LIGHT VALVE PROJECTOR
- MATRIX ADDRESSED FLAT PANEL
  - PLASMA
  - LED
  - LIQUID CRYSTAL
  - ELECTRO LUMINESCENT
  - MAGNETIC PARTICLE

OPTICS TECHNOLOGY

- DIRECT
- PORTED
- HEADS UP
- HELMET MOUNTED
- PROJECTED

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Figure 60. Subsystem Options – Controls and Displays

2.5.1.2 Selected Approach - Electroluminescent flat panel technology was selected (Figure 61) for the alphanumeric/graphic display primarily because of its low power and high performance which makes it very attractive for displaying subsystem status information, caution and warnings and, task descriptions for orbital activities. A computer entry keyboard operates in conjunction with this panel for verifying data input values. Specific information displayed at any given time is determined according to a priority interrupt system with caution and warning parameters as necessary.

A conventional direct display black and white TV was chosen as baseline for video information (CCTV) because of its reasonable power level and proven state of development. Color TV is not warranted at this time but is worthy of evaluation by simulation. A baseline C&D panel arrangement has been developed but final selection will be the result of evaluation of alternate designs by simulation.

2.5.2 Console Function, Layout and Area

The controls and displays (C&D) for the closed cabin cherry picker were developed with the objective being minimum panel depth, volume and power while providing all necessary functions. The selected console arrangement is illustrated in Figure 62 with corresponding functions, dimensions and power allocations given in Table 21. The philosophy used in developing the console arrangement was to limit the equipment directly in front of the astronaut to that absolutely requiring visibility while performing out-the-window operations.

The Lunar Module, Shuttle, and Manned Maneuvering Unit equipment were extensively used for defining functions and corresponding panel area allocations. State-of-the-art advances in display capabilities were investigated as an area which can greatly reduce total C&D volume and power by integrating different display functions. The outcome of this analysis resulted in the selection of a flat panel display, such as the electro-luminesent type, for most alphanumeric and graphic functions. The only separate panel functions selected are a five item caution and warning display, voltmeter, temperature and pressure indicators. The computer entry keyboard operates in conjunction with the flat panel display for verifying data input values. Callup of particular information is made via the keyboard. The specific information displayed at any given time is determined according to a priority interrupt system.

- ELECTROLUMINESCENT FLAT PANEL DISPLAY FOR ALPHANUMERIC/GRAPHIC (50 W AVG PWR)
  - SUBSYSTEM STATUS
  - CAUTION & WARNING
  - TASK DESCRIPTIONS
- CONVENTIONAL DIRECT DISPLAY B&W TV
- BASELINE PANEL SELECTION

ISSUES TO BE RESOLVED

- SIMULATION: KEY TO CONTROLS & DISPLAYS INTEGRATION
  - COLOR TV EVALUATION
  - PANEL ARRANGEMENT
  - HELMET-MOUNTED DISPLAY EVALUATION
  - CCTV CAMERA LOCATION TRADES, OPTIONS SHOWN BELOW

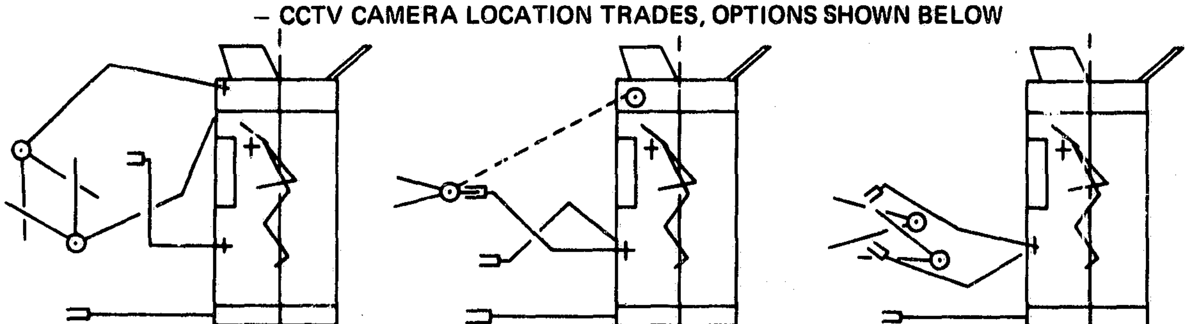

Figure 61. Controls and Displays – Approaches

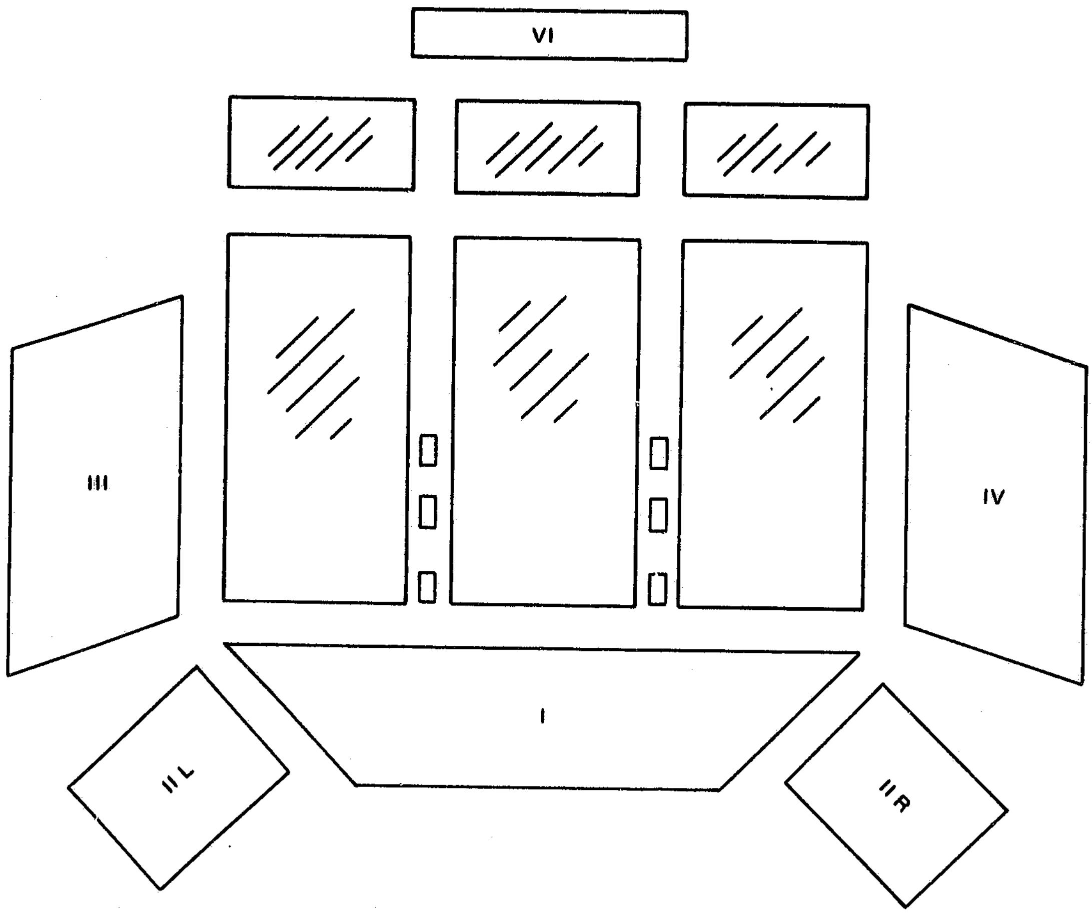

Figure 62. Closed Cherry Picker – Controls and Displays Panels

TABLE 21

CLOSED CHERRY PICKER – CONTROLS AND DISPLAYS

FUNCTION	PANEL AREA (in.^{2})	DIMENSIONS (in.) W	H	D	AVG POWER (W)
I FRONT PANEL	(297)				
• ALPHANUM./GRAPHIC	224	8	7	6	50
• KEYBOARD	36	6	6	6	5
• CRANE CONTROL	15	5	3	3	5
• CAUTION & WARNING	10	2	2,5	2	–
• MASTER STOP	4	1	4	2	–
• CCTV CONTROL	8	4	2	2	–
II L FRONT LEFT PANEL	(44)				
• TTCA	–	–	–	–	–
• AUDIO	28	7	4	3	5
• INTERIOR LIGHTS	16	4	4	3	40/20
II R FRONT RIGHT PANEL	(51)				
• ACA	–	–	–	–	–
• GRAPPLER CONTROL	15	5	3	3	–
• EXTERIOR LIGHTS	36	6	6	3	–
III L LEFT PANEL	(430)				
• MASTER CONTROLLER	144	12	12	6	(50)
• EPS CONTROL	90	18	5	6	10
• CIRCUIT BREAKERS	96	24	4	3	–
• ENVIRON. CONTROL	100	10	10	6	10
IV RIGHT PANEL	(310)				
• MASTER CONTROLLER	144	12	12	6	(50)
• COMM	70	10	7	3	5
• CIRCUIT BREAKERS	96	24	4	3	–
V RIGHT UPPER	(154)				
• CCTV (2)	154	11.5	7	12.5	(100)
VI OVERHEAD PANEL	(60)				
• RENDEZ. & DOCK	60	12	5	3	(25)
				TOTALS	315 MAX 110 MIN

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Two minimum-package closed circuit television (CCTV) monitors are included in the console arrangement with either direct viewing or reflected viewing dependent on available cabin space.

Alternative video display approaches which are available using CRT technology, because of its projection capability, include HUD and helmet mounted displays. The former has been tentatively rejected because it generally requires a CRT mounted where console panel I is located thereby using a panel location needed for other functions. The helmet mounted display using an opaque visor for projecting video to be an attractive approach which will be considered as an alternative to the CCTV monitors. This system would allow the astronaut to change from direct viewing to TV viewing by flipping down his visor. Evaluation of this approach relative to conventional TV monitors requires simulation.

2.5.3 Dexterous Manipulator Controller

Three general types of control devices are available for operation of dexterous manipulators. A position control device, called a master, replicates the degress of freedom (DOF) of the hand (end effector) of the slave (working) dexterous arm. The motions of the master arm are proportional to the slave arm (frequently, a ratio of 1:1). This type of control can be operated with or without bilateral force reflection (BFR). A hand controller is a second type of control device. A hand controller can respond to 6 DOF of either displacement or force control. However, the force inputs are generally used to implement a rate control system, not a position control or BFR system. A third type of control utilizes discrete switches (or dials) for each DOF. The switches are used for an open loop rate control system. An extensive comparison of these three control devices was performed in Reference 3 and summarized in Reference 4. Figure 63 (from Reference 4) summarizes the results of these tests for eight different tasks. The evidence is overwhelmingly in favor of master/slave control. For the simplest task (No. 8), the hand controller directed action took twice as long and the switch box directed action took three to five times as long as the master/slave. For more complex tasks, these ratios are substantially higher (e.g., 7 to 1). It should be noted that these tests utilized a master/slave controller without force feedback (no BFR) but permitted unrestricted vision from any angle or distance. The conclusion drawn from this work is that the most efficient technique for performing

LEGEND

MASTER/SLAVE (WITH NO FORCE FEEDBACK)

RMRC & 6 DOF HAND CONTROLLER

RC & 6 DOF HAND CONTROLLER

RMRC & SWITCH BOX

RC & SWITCH BOX

WHERE RMRC = RESOLVED MOTION RATE CONTROL
RC = RATE CONTROL

TIME CONTROL = TASK COMPLETION TIME DIVIDED BY MASTER/SLAVE TASK COMPLETION TIME (M/S = 1.0)

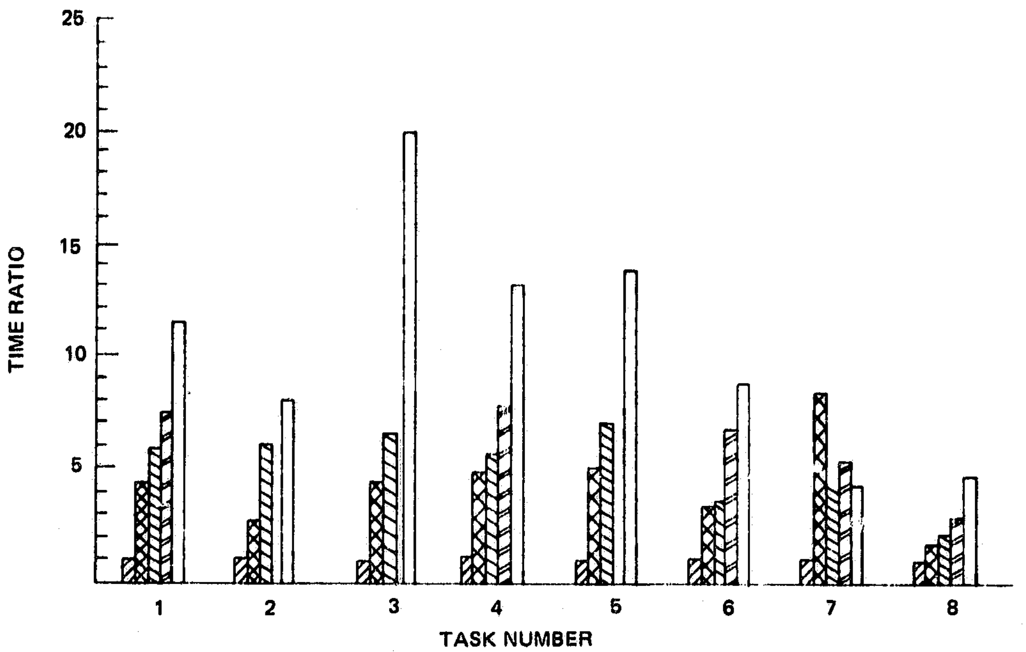

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Figure 63. Results of Evaluation and Comparison Tests

a manipulator task is to simulate the task with human limbs and have a dexterous arm reproduce the significant motions. Consequently, a master/slave controller is selected for MRWS dexterous arm operation.

An argument for indexing between master and slave is presented in Paragraph 2.3.4. Because indexing is available, the master controller is designed to have the smallest possible motion for efficient performance of manipulator tasks. At a worksite, maximum productivity results when the ratio of slave motion to master motion is unity. (This ratio is measured at the center of the hands or end effectors.) Consequently, a 10-in. cube was selected as the allowable translation limits for the master hand. This provides a moderate size useful volume which does not excessively restrict an operator's natural motions. The actual size and shape of a "minimum" control volume will require further study of cabin arrangements and simulator tests of operator efficiency. As described in Paragraph 2.3.7, computer generated coordinate transformations will maintain force and motion references at the master for all orientations of the slave and master.

Because coordinate transformation is available, the master and slave do not have to be similar. A master control which consumes a minimum amount of cabin volume is desirable. Design studies of volume efficient masters should be conducted in the future. For the present, a "replica" master, which is smaller but proportional to the slave arm, is assumed for the flight vehicle.

To follow the motions of an operator's hand and arm, the master controller must have similar DOF. This implies at least the following master controller DOF: upper arm pitch and roll, elbow pitch, forearm roll, and wrist pitch and yaw. Six DOF are the minimum required to control the position and attitude of a body (e.g., an end effector). Conversely, a given position and attitude of the control handle determines the unique locations of all components of a 6 DOF master controller. However, the slave arm includes a seventh degree of freedom, shoulder yaw (see Paragraph 2.3.4). To accommodate this additional DOF, a constraint between the elbows of master and operator was considered. Although this slip-fit "sleeve" is valuable during reach-in and reach-around activities, it may be fatiguing and tends to inhibit an operator from releasing the master and performing another task. Consequently, it was rejected. Because shoulder yaw is an infrequent operation which consumes a large volume of cabin space, slave shoulder yaw will be controlled by a

separate operator controlled switch. Thus, this DOF is absent from the master controller. Slave wrist rotation will be controlled in two modes. Normal operation is through rotation of the master wrist utilizing twist of operator's forearm and upper arm. However, special operations of twisting the slave wrist utilize a rate control switch on the master controller. This second control mode permits large twist angles for unscrewing type operations. The configuration of the hand portion of the master and its control techniques (for a variety of currently unknown end effectors) will be determined at a later date.

Design studies of various orientations of a replica master were conducted. With an anthropomorphic arrangement - master forearm and upper arm parallel to operator's with master shoulder behind operator's shoulder - a master length of 36 in. (forearm plus upper arm) is required for control excursions over a 10-in. cube. It should be noted that this arrangement allows much larger control excursions. For a reflected anthropomorphic arrangement - same as anthropomorphic at neutral position except master shoulder is below the forearm - a master length of 30 in. is required. For this arrangement, control excursions are limited to the 10-in. cube. An anti-anthropomorphic arrangement - master shoulder below operator's forearm and master forearm approximately perpendicular to operator's forearm - permits the use of the smallest master with potentially very large control excursions. A master length of 24 in. has been selected as representative of the smallest length for a device of this complexity.

A master/slave controller can be used exclusively as a position controller with only visual feedback or it can be used with a force feedback system supplementing visual feedback. There are three distinct advantages to a force feedback system like bilateral force reflection. BFR permits two arm cooperative tasks, reduces collision damage and increases productivity. If two slave arms without BFR are holding the same rigid body, translation of the body becomes extremely difficult. Because the command inputs for the two arms can never be precisely the same (for either position control or resolved motion rate control), the body is strained and slippage occurs between body and end effectors. For fragile bodies, damage may result. Rotation of a body is even more difficult because the control inputs for each arm must be compatible with a single center of rotation. These difficulties are removed when BFR is used. With force reflection, the operator is able to sense and easily correct

the tendency of the two slave arms to fight one another while achieving the desired motion. The second advantage of BFR is known because of earth laboratory experience with manipulators. In general, collisions between a slave arm and a laboratory facility have been non-damaging to either object with BFR. For installation tasks, collisions are unavoidable. The collisions are aggravated without BFR. Reference 5 reported "that it was virtually impossible to load the container without an error in the resolved motion rate control mode." An "error" consisted in unintentionally displacing the table which supported the container a distance of 1 to 2 in. Without BFR, operator judgement errors will produce impacts while the slave arm motors are still forcing the arm toward impact. These collisions may be more damaging than comparable BFR collisions. The third advantage of BFR is increased productivity. References 6 and 7 indicate that a position controller (master/slave) without BFR requires between four and seven times more time to complete specific tasks than the same controller with BFR. Because productivity is the most powerful factor in the cost of very large space structures, BFR is required for MRWS manipulators.

The maximum velocity input at the center of a master handle is a function of the type of indexing and the size of the controller's working volume. For all types, an upper limit is the fastest motion of a human hand: about 75 cm/sec (30 in./sec.) The maximum tip force reacted by the controller is in the range of 22 to 32 Newtons (5 to 7 lb). This range is a compromise between operator fatigue and the force level required for useful BFR. The preferred value will be determined during simulator tests.

2.6 ELECTRIC POWER SYSTEM

2.6.1 Power Source - Remote versus Local

Because weight and volume are critical factors in the design of the closed cabin and cherry picker arm, it would be advantages to locate the electric power source external to closed cabin and cherry picker arm and supply the power via hardwire attached to the cherry picker arm to the closed cabin. The fuel cells/batteries would be located on the fixed base or railed vehicle. In case of emergency, battery power source would be located in the aft equipment bay to power critical subsystems (Environmental Control and Life Support and Communications) until rescue of the astronaut is completed in approximately 1 hr.

2.6.2 Electrical Loads

A summary of electrical loads by subsystem is listed in Table 22.

2.7 CREW ACCOMMODATIONS

2.7.1 Rescue Provisions (Cabin MRWS)

2.7.1.1 Discussion - Provisions for the following contingencies must be made:

- Loss of pressure
- Hatch malfunction
- Structurally attached MRWS immobile
- Free flyer loss of rendezvous/docking capability.

Crew action in the event of pressure maintenance capability loss (e.g., cabin puncture) could be donning of an Extravehicular Mibility Unit (EMU) or Personnel Rescue System (PRS). The MRWS must provide redundant pressure capability to permit time for donning. The EMU permits unaided return to a habitation module in most instances, contrasting to the PRS that always requires an EVA astronaut or equivalent for assistance. Stowage volume for the PRS is $\frac{1}{4}$ of that required for the EMU as illustrated in Figure 64. The PRS has 1 hr capability versus 8 hr for the EMU.

Rescue could be accomplished by docking to the disabled MRWS or EVA space transfer. In the event of a hatch malfunction, an alternate egress capability must be provided. If docking is impossible, then crew transfer must be accomplished using either the EMU or PRS. Several means of transfer are available; free flyer MRWS, MMU, or clothesline tether system.

If the contingency is malfunction of the MRWS crane, then different approaches are possible for rescue. A free flyer or another cherry picker could repair the MRWS crane to allow the crew to egress in the normal manner. When repair is impossible due to MRWS consumable time limitations, then EVA egress could be done as previously described.

Rescue of a free flyer MRWS after loss of rendezvous capability could only be achieved by another free flyer (probably OTV) rendezvousing with the disabled craft and either returning it to the work base or transfering the crew to the rescue vehicle. Loss of docking capability means implementing space transfer requirements.

TABLE 22

ELECTRICAL LOADS SUMMARY

EQUIPMENT	AVERAGE POWER (W)	EQUIPMENT	AVERAGE POWER (W)
CABIN LOCATION		AFT BAY LOCATION	(202)
• ECLS	(794)	• EPS	
- CONDENSATE FAN/PUMP	39	- INVERTER	10
- CABIN FAN	215	- CONT/DISTRIB BOX	5
- HEAT EXCH PUMP	180	- REGULATOR	10
- HEAT EXCH TEMP VALVE	35	• COMMUNICATIONS	
• COMMUNICATIONS		- UHF RECEIVER	33
- HEADSET/MIC	5	- VHF TRANSMITTER	31
• ILLUMINATION		- SIGNAL PROC UNIT	13
- CONTROL BOX	5	- RANGE TONE TRAN ASSY	5
• CONTROLS & DISPLAYS	315	• INSTRUMENTATION	
EXTERNAL LOCATION	(1800)	- SIGNAL COND UNIT	16
		- PULSE CODE MOD	11
• DEXTEROUS ARMS (2)	400	- CAUTION/WARNING ASSY	13
• CCTV		• DEXTEROUS MANIP	
- CAMERA (2)	300	- DRIVE ELECTRONICS	15
- BOOM	200	• CCTV	
• ILLUMINATION		- ELECTRONICS	20
- LIGHTS (2)	500	• GRAPPLER	
• GRAPPLER ARMS	150	- DRIVE ELECTRONICS	20
• TOOLS	250	TOTAL	2.796 kW

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2.7.1.2 Recommendations - The MRWS must carry provisions for crew safety in the event of cabin pressurization loss and for the crew to effect an EVA transfer to a rescue vehicle. During large structure construction, the MRWS operate at considerable distance away from the habitability module requiring transportation modules. Therefore, assistance will always be available to assist an MRWS crew if needed. Based on the premise that the MRWS cabin design permits shirt sleeve operations, an EMU would not normally be carried. If it is part of the normal compliment of equipment to permit scheduled EVA activities, then the EMU would be available for contingency operations. Because the PRS requires less volume for stowage than the EMU and the fact that assistance for space transfer is available, it is recommended that PRS(s) be stowed in the MRWS cabin for pressure loss/EVA transfer contingencies. This implies that the MRWS pressure is maintained while the crew dons the PRS and the hatch(s) must be capable of unlatching from the outside of the MRWS. To eliminate prebreathing, the design concept PRS operating pressure of 5 psi should be increased to 8 psi.

Hatch malfunction safety criteria could be accomplished in one of two ways. The hatch could be designed with a backup removal system such as strip charge that cuts the hatch free of the MRWS structure or add a second egress hatch. The approach selected could be governed by other factors that drive the cabin design.

2.7.2 Tools

The following is a list of typical construction tools that will be required by the closed cabin MRWS to perform the various construction tasks analyzed in Appendix A:

- Ultrasonic welding machine (900 W 1 sec)
- Impact tool for punching holes
- Rotation tool for drilling holes, torqueing bolts and screws (200 W) (50 in.-lb torque)
- Vise-type tool for crimping or swaging joint connections
- Cutters for cutting wire cable
- Tool for connecting electrical umbilicals connectors
- Terminal type general tool kit containing pliers, wrench sets, screwdrivers sets, cutting tools, hammers

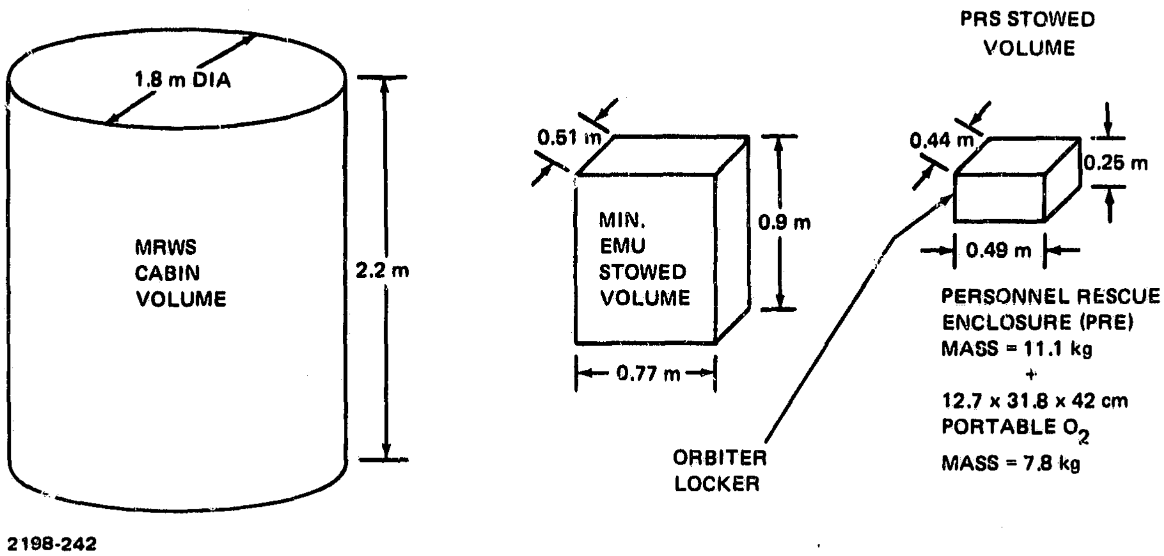

Figure 64. Comparative Volume of MRWS Cabin, EMU and PRS

- Tube connector type for flaring or swaging plumbing tubing
- Alignment instruments such as laser, transit, and mechanical jigs
- Checkout devices such as X-ray equipment for welds, ultrasonic inspection, electrical continuity, and fluid leak detectors.

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Section 3

CRANE TURRET DELTA REQUIREMENTS FROM CLOSED CABIN

3.1 INTERFACES

MRWS Crane Turret Configuration

Table 23, summarizes the five possible configurations for the MRWS and crane turret combinations that require a comparative trade analysis based on the task analyses for the construction of the microwave antenna (TA-1) and photovoltaic solar collector development (TA-2) spacecraft. A perusai of Table 26, however, does not produce an immediate and obvious optimum configuration, except in terms of bearing considerations: combination A, zero rotating bearings; combinations C and E, one rotating bearing; and combinations B and D, two rotating bearings. In all cases, two crane functions are required: one to move the payloads to their required interfaces and the other to support an open MRWS cherry picker. For analysis purposes, the MRWS crane turret shown conceptually in Figure 65 can be used to define the constrained rotations of the MRWS, base, and crane.

A limited rotation capability for the MRWS cabin, and the crane turret (base) of 360°, i.e., ±180°, is considered essential to minimize the interface problems caused by slip rings, yet still provide complete vision coverage in azimuth. The DOF rotation requirements for the crane arms shown in Table 24 are derived from considerations to provide the maximum work zone with the minimum interface complexity.

For the MRWS cabin and crane turret configuration, combination E has been selected over the other combinations. Table 25 presents a comparative summary of the various issues considered in the evaluations.

The weight of the rotating bearing is about 300 lb; therefore, it should be minimized from the beginning, i.e., cabin and crane combinations limited to no rotating bearing or at most one bearing. This consideration immediately limited the considerations to combinations A, C, and E. Additional window requirements for fixed cabin configurations and the associated heat exchanger and screening problems clearly favor a cabin and crane turret combination that rotate as a unit. Because this

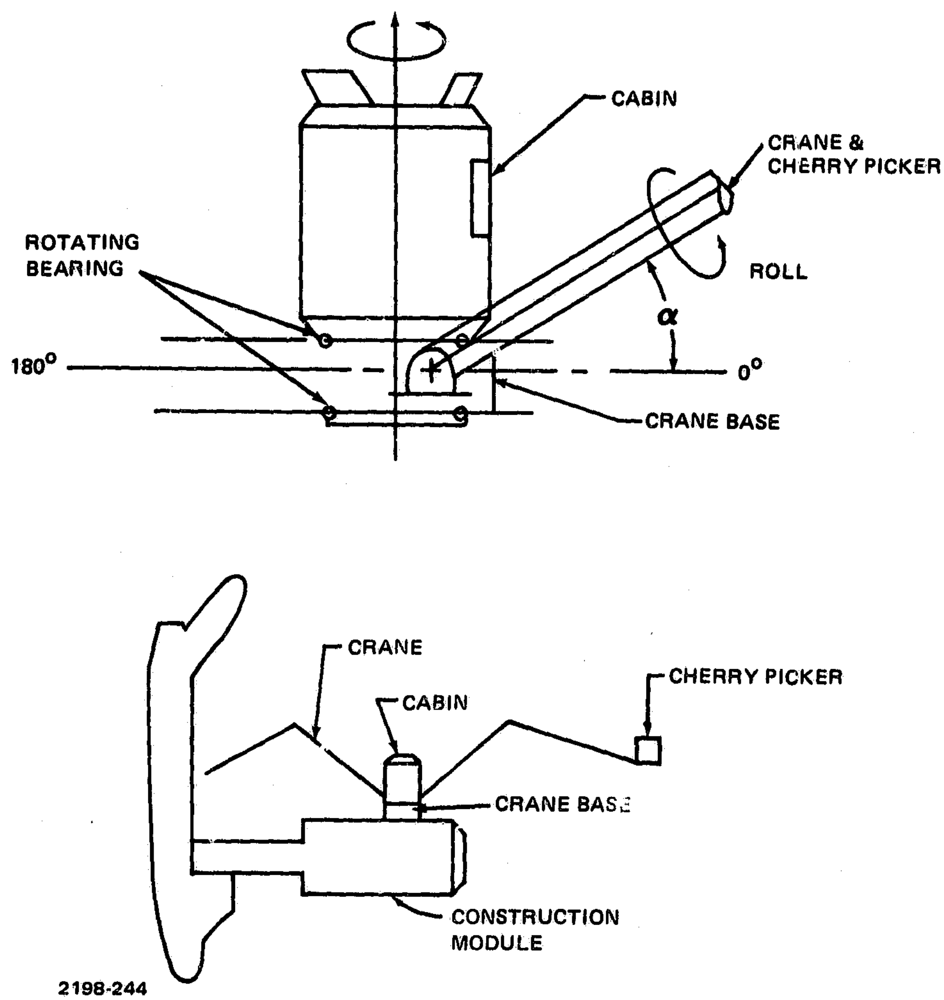

Figure 65. MRWS Crane Turret Combination

TABLE 23

MRWS CABIN AND CRANE TURRET COMBINATIONS

COMBINATION	CABIN	BASE
A	FIXED	FIXED
B	FIXED	MOVEABLE
C	MOVEABLE	FIXED
D	MOVEABLE	MOVEABLE
E	MOVEABLE AS A UNIT	

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TABLE 24

MRWS CABIN, CRANE TURRET AND CRANE ARM ROTATIONS

ROTATING ELEMENT / COMBINATION	CABIN	TURRET	CRANE ARM PITCH	CRANE ARM AZIMUTH (B)	CRANE ARM ROLL
A	0	0	$0^{\circ} \rightarrow +150^{\circ}$	$-30^{\circ} \rightarrow +180^{\circ}$	$0^{\circ} \rightarrow +90^{\circ}$
B	0	$\pm 180^{\circ}$	$0^{\circ} \rightarrow +150^{\circ}$	$-30^{\circ} \rightarrow +180^{\circ}$	$0^{\circ} \rightarrow +90^{\circ}$
C	$\pm 180^{\circ}$	0	$0^{\circ} \rightarrow +150^{\circ}$	$-30^{\circ} \rightarrow +180^{\circ}$	$0^{\circ} \rightarrow +90^{\circ}$
D	$\pm 180^{\circ}$	$\pm 180^{\circ}$	$-30^{\circ} \rightarrow +90^{\circ}$	$-30^{\circ} \rightarrow +90^{\circ}$	0
E	AS A UNIT $\pm 180^{\circ}$		$-30^{\circ} \rightarrow +90^{\circ}$	$-30^{\circ} \rightarrow +90^{\circ}$	0

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TABLE 25

COMPARATIVE SUMMARY OF MRWS CABIN AND CRANE TURRET ANALYSIS

COMBINATION / ITEM CONSIDERED	A	B	C	D	E
• ASTRONAUT VISION	ADDITIONAL WINDOWS IN CABIN REQUIRED	ADDITIONAL WINDOWS IN CABIN REQUIRED	360° VISION ZONE PROVIDED	360° VISION ZONE PROVIDED	360° VISION ZONE PROVIDED
• CCTV	EXTENSIVE TV COVERAGE REQUIRED	EXTENSIVE TV COVERAGE REQUIRED	NORMAL TV COVERAGE	NORMAL TV COVERAGE	NORMAL TV COVERAGE
• BEARING	NO BEARINGS REQUIRED	2 BEARINGS REQUIRED	1 BEARING REQUIRED	2 BEARINGS REQUIRED	1 BEARING REQUIRED
• WORK ZONE	LIMITED	LIMITED	$\pm 180^{\circ}$ FOR CRANE	$\pm 180^{\circ}$ FOR CRANE	WORK ZONE AND VISION ZONE THE SAME
• CONSTRUCTION MODULE INTERFACE	SIMPLE-DIRECT CONNECTIONS	INTERFACE MODERATELY COMPLEX	INTERFACE MODERATELY COMPLEX	PRESSURIZATION & SERVICE INTERFACE COMPLEX	PRESSURIZATION & SERVICE INTERFACE COMPLEX
• MISCELLANEOUS	LIMITED CAPABILITIES FOR DIRECT VIEWING & CONTROLLING	LIMITED CAPABILITIES FOR DIRECT VIEWING & CONTROLLING	CONTROL CABIN ROTATION FOR VIEWING	COMPLEX CONTROLS-MOVE BOTH CRANE & CABIN	NORMAL CONFIGURA-TION FOR EARTH BASED DESIGNS & MINIMIZES CONTROLS

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approach also minimizes the requirements for dual controls and is the normal construction type crane used on earth, it was baselined as the MRWS cabin and crane turret configuration.

3.2 MECHANICAL

3.2.1 Crane Control - Resolved Rate versus BFR

Manual control of the crane will be through one or more multiple degree-of-freedom controllers. The nature of the control devices depend on the type of control method chosen. There are two potential methods of control applicable to the crane viz., resolved rate control (RRC) and the bilateral force reflecting (BFR) position control. The relative merits of these are discussed below.

3.2.1.1 Resolved Rate Control - Resolved rate control is a rate control system where the motion of the tip of the crane or some other pre-specified reference point can be translated and rotated at velocities specified by command inputs. The translational and rotational velocities are specified through a suitable control input device. Based on these, the required joint rates are computed and transmitted to the joint servos of the crane. The crane joints are operated in the rate mode. The control input device may be either a pair of 3 DOF Apollo-type hand controllers (a Translational Hand Controller - THC, and a Rotational Hand Controller - RHC) or a single 6 DOF hand controller. The RRC permits control of the crane in any one of several coordinate systems. Some of these are:

- End effector coordinate system
- Payload coordinate system
- Crane base coordinate system
- Line-of-sight coordinate system (for controlling a second crane from the cherry picker for activities involving two cranes).

The salient features of the RRC are the following:

- Ability to operate in any selected coordinate system
- Ability to operate at varying speeds (coarse and vernier mode)

- No force feedback available in RRC. Force feedback can be implemented in RRC in several ways. The forces and moments at the end effector/crane interface can be measured and displayed to the operator, or fed to hand controllers with active servo joints. An alternative approach is to accommodate the measured forces by feeding them to the crane joint servos
- The controllers are compact
- Two 3 DOF controllers require two-handed operation but eliminates all cross coupling between the various DOF. A single 6 DOF hand controller can be used for one-handed operation but it is difficult to eliminate cross couplings between the DOF completely. A possible alternative approach to single-handed operation is to have a single 3 DOF hand controller with a switch to designate it as either a translational or rotational controller. The crane will be operated alternatively in a hawk mode (pure translation with fixed orientation of end effector) and in Euler mode (pure rotation with no translation). Several manipulators can be controlled serially from the same controller(s)
- The implementation of RRC requires a computer and software
- RRC is similar to flying the Orbiter RMS
- Because of the seven joints in the crane, a pseudo inverse approach will be used in the resolved rate algorithm. The presence of the elbow roll joint eliminates the shoulder yaw motion singularity. The wrist singularity is still present (it can be eliminated by providing a roll joint in the lower arm).

3.2.1.2 Bilateral Force Reflecting Control - This is a position control system with force feedback consisting of the crane or slave arm and a control arm, or master arm. The master arm must replicate the slave arm having essentially same characteristics except for its size. Bilateral force reflection means that forces and moments acting on either the master or the slave are sensed at the other. In general in master-slave systems, the master joint angles and the corresponding slave joint angles are controlled to be in 1:1 correspondence. BFR manipulator systems have been used in earth-based applications where the master and slave are about the same size. In the context of using a BFR concept with the crane, the following are the salient points:

(1) To be compatible with the operator's arm, the master must be 0.75-m long when fully extended. With seven joints, the master will be complex and its motion will be encumbered by the size and the layout of the control cabin. Reducing the size of the master will amplify the scale ratio problem discussed below.

(2) With a master arm of 0.75-m and a crane of 35 m we obtain a scale ratio of 1:46.66. Because the joints in the master and slave are coupled one to one, the operator's inputs will be magnified by 46.66 at the crane end making precise positioning difficult.

(3) To obtain full range of motion of the crane, the operator could get into some uncomfortable and awkward positions with the master controller because the controller would have to be positioned in the same posture the slave would assume.

(4) The problems outlined in (2) and (3) above can be overcome by introducing variable position ratio and indexing. The variable position ratio allows the ratio of master movement to the slave movement to be varied. Thus, for large motions of the crane the high ratio of 1:46.66 would be used where 1-cm movement of the master would give a 46.66-cm movement of the crane. For precise positioning, a lower ratio such as 1:5 would be used for a 1-cm movement of the master to provide a 5-cm movement of the crane. To maintain the same motion ratio for translations and rotations about three orthogonal axes, the resolved rate approach needs to be used in the BFR system for both the salve and master. Thus, the implementation of variable position ratio will be very complex.

Indexing is a means of which the master can be repositioned for maximum operator convenience regardless of slave position. It also permits gross motion of the crane in low position ratios.

Both indexing and variable position ratio requirement for the BFR system for the crane has the major disadvantage of destroying the spatial correspondence between the master and the slave, which is basic to the master-slave system.

(5) BFR provides force feedback to the operator which is essential for assembly type tasks. Force feedback causes operator fatigue during extended work peridos. This problem can be alleviated by providing a variable force reflection ratio where the force required at the master to produce a given force at the slave can be varied.

(6) The wrist motion singularity encountered in the RRC is encountered in the BFR as well.

(7) Implementation of BFR does not require a computer. Implementation of variable position ratio and indexing requires a computer and software.

(8) Spatial correspondence between the master and slave will be lost if the master is mounted in a control station attached to the slave and rotates as the slave moves. Thus, BFR cannot have spatial correspondence if the controller is mounted in the cherry picker or in the cabin at the crane base rotating with the crane.

3.2.1.3 Control Method Recommendation - Based on the above observations, the RRC is recommended. To overcome the lack of force feedback, it is recommended that one of the methods discussed above for force feedback in RRC be implemented after evaluating their relative merits.

3.2.2 Controller Configuration

3.2.2.1 BFR Controller - If a BFR control concept is selected, the controller will be geometrically similar to the crane with respect to the number of joints, order of joints, joint travel, and ratio of link lengths. All joints will be servo controlled with the motors sized to produce a tip force of 110N when the controller is straight. The controller will be 0.75 m when fully extended. Maximum joint rates will be the same as those for the crane (Table 26). The ratios of the distance between joints to the overall length will correspond to those of the crane. The maximum torque rating of the joints will be 1/93.333 of the torque rating of the corresponding crane joints. The total power required for the controller will be 24.25 watts.

3.2.2.2 Resolved Rate Controller - If a Resolved Rate Control concept is selected, there are three options for the controller configuration:

TABLE 26

CRANE POWER REQUIREMENTS

JOINT	MAXIMUM TORQUE (Nm)	MAXIMUM JOINT RATE (rad/sec)	POWER (W)	COMMENTS
SH. YAW	7700	0.017	323.2	
SH. PITCH	7700	0.017	323.2	
EL. ROLL	4312	0.03	319.4	JOINTS ASSUMED TO HAVE THE SAME TORQUE & SPEED REQUIREMENTS
EL. PITCH	4312	0.03	319.4	
WR. PITCH	924	0.143	326.2	ALL JOINTS ASSUMED TO HAVE THE SAME TORQUE & SPEED REQUIREMENTS
WR. YAW	924	0.143	326.2	
WR. ROLL	924	0.143	326.2	
		TOTAL	2263.8	10% DERATING IN SPEED 10% DERATING IN TORQUE 50% MOTOR & ELECTRONICS EFFICIENCY

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- Two 3 DOF hand controllers (similar to SRMS - a translational hand controller, THC for the lefthand operation, and a rotational hand controller RHC for righthand operation)
- A single 6 DOF hand controller which is not geometrically similar to the crane. Careful design is required to reduce cross coupling between various DOF. The 6 DOF provide the six command inputs for the translational and rotational velocity components
- A single 3 DOF hand controller with a switch to assign it for translation and rotation commands. The system will be operated in a hawk mode (pure translation) and in a Euler mode (pure rotation) alternately.

Two hand controller approaches require two-handed-operation, but the operator is free to remove one or both of his hands from the controller unless he is tracking a moving target. In the Hawk/Euler mode approach, simultaneous translations and rotations are not possible. In all of the above approaches, the joints will contain position sensors to generate command inputs along with springs to provide return to null and dashpots to provide damping.

Preliminary specifications for the DOF in the controllers are:

- ±15° rotary displacement full scale
- ±1.25 cm linear displacement full scale
- 20 N maximum force at full displacement (linear)
- 2 N breakout force
- 1 Nm maximum torque at full displacement (angular)
- 0.1 Nm breakout torque
- Damping TBD.

Force feedback can be introduced by mechanizing the joints with suitable servo systems.

3.3 ENVIRONMENTAL CONTROL AND LIFE SUPPORT

Blowdown versus Pumpdown for Repeated Operation

Evaluation - For the crane turret MRWS application where cabin depressurizations may be scheduled frequently (airlock operation), a trade study shows that cabin pumpdown is advantageous on the basis that the gas is pumped into an attached space construction base with a large volume (2500 ft^3) and a similar environment to the MRWS.

A pumpdown time of 15 min to 2.0 psia final pressure results in a compressor peak power requirement of 3 kW. (2.0 psia is chosen as a minimum practical pressure compatible with single stage compression ratio to 14.7 psia.)

Recommendation - MRWS pumpdown should be used when repeated cabin depressurizations are planned.

3.4 CONTROLS AND DISPLAYS

CCTV Requirements and Location

The CCTV system will assist the space crane operations by improving visibility of areas that cannot be seen by the crane operator directly. The CCTV views will be used for grappling, for viewing the crane and surrounding areas to avoid collisions, and for other crane-related operations.

Two TV cameras (TVC), one mounted at the elbow on the lower arm, and the other mounted on the wrist will be used. Additional cameras may be mounted on the crane cabin/turret and the closed cabin cherry picker. The wrist TVC will be used for docking and grappling as well as to detect collisions of crane with the surrounding when in cherry picker mode. The elbow TVC will be used to detect impending collisions between the crane, cherry picker, payload being handled and the surroundings. Two TV monitors will be provided located near the C&D panel so as to minimize head and eye movements when changing from direct view to monitor view during crane operations. The position of the monitors shall be based on human factors studies with a realistic cabin mockup and C&D panel layouts. The requirements on the CCTV system will be heavily influenced by the end use of the crane. Preliminary requirements are specified below with parameters to be determined identified for further study.

Color versus Monochromatic - A study is required to determine the advantages and cost in using a color CCTV system as against a monochromatic system.

Monitors - The screen shall be TBD diagonal, controls shall be provide for brightness and contrast. The monitors shall be compatible with all TVC to be used in the space crane program. Split screen operation for presenting two views on a single monitor is preferable. The two TV monitors shall be located based on human factors studies for optimum viewing, minimum eye/head movement and crew cabin compatibility.

TV Cameras -

- Field of View - The lens shall have a maximum diagonal FOV of TBD degrees and a minimum diagonal FOV of TBD degrees
- Focus - At the widest FOV, the lens will provide sufficient resolution to allow the television camera to resolve an object size corresponding to TBD TV lines at a distance of 0.5 m and have a depth-of-field sufficient to maintain the same resolution from TBD m to TBD m without readjusting the focus on the iris. The resolution and depth of focus must be determined on the basis of scenes and associated fine structure that will be encountered by the TV camera during the operation of the crane.
- Lens Interchangeability - The TV lens assembly will have the capability of removing and replacing lens on orbit to enable the TV camera to view various types of scenes likely to be encountered (e.g., zoom, wide angle, telephoto, closeup, etc.). A multiple lens head with indexing is another possible approach.
- Pan/Tilt Capability - The camera will have pan/tilt capability of ±180° in pan and tilt. Both pan and tilt shall have a slow slew rate of TBD deg/sec and a fast slew rate of TBD deg/sec. Provision will be made for auto return to null position. In the event of pan or tilt drive failure, the system can be forced to null position with TBD Nm torque.

TV Lighting - A light will be provided with each TV camera mounted behind and the TVC and bore-sighted to intersect the camera line-of-sight at TBD m. The light shall not cast any shadows in the field-of-view of the camera. The lights will be used for operations when the sun is blocked by spacecraft or earth.

The lamps shall be of a narrow cone diffused flood light type (tungsten, mercury discharge, quartz iodine or other suitable type). The chromaticity of the lamp shall be white with a colour temperature of 2800°K for tungsten incandescent and 3200°K for other types. The cone of radiation shall be 5° greater than the maximum field of view of the TV camera. The intensity distribution across the cone shall be TBD. The intensity of the light shall be sufficient to provide a minimum of TBD illumination at a distance of 35 m from the light. The light shall be mounted so as to move with the TV camera during pan and tilt.

CCTV System Controls - The following CCTV controls shall be provided:

- TV view selection
- Split screen mode selection
- Camera controls for pan/tilt, zoom, iris, ALC, and gamma correction
- Provision for auto return to null position for the TV cameras
- Switches for lights.

Reticle - A reticle may be provided to align the camera with targets, and alignment and sighting aids.

3.5 ELECTRICAL POWER

Crane Power Requirements

Based on the tip force requirements and the dimensions of the crane, the maximum torque requirements for the various joints can be computed. From the unloaded tip velocity, the maximum speeds of the joints can be computed. The following assumptions are made to obtain the data shown in Table 26.

- Maximum joint torque results at 90% of motor stall torque
- Maximum joint speed results at 90% of motor no-load speed
- Efficiency of motor and electronics 50%. To use the stopping distance as the criteria for joint torque rating and power requirement estimates, details of the mass distribution of the crane and the payload (MRWS or other payloads being handled by the crane) is required.

Section 4

FREE FLYER DELTA REQUIREMENTS FROM CLOSED CABIN

4.1 STRUCTURE

4.1.1 Additional Equipment

The equipment shown in Table 27 comprise the additional components that must be added to the closed cabin subsystems in Table 14 to meet Free Flyer requirements.

4.1.2 Jet Mounting Locations

Alternate jet configurations and locations were evaluated which provide both rotational and translational control for the free flyer. The objective of the study was to provide combined rotation and translation functions from the same thrusters. It was also considered desirable that the selected concept avoid as much as possible thruster plume impingement on the cabin manipulators, cargo platform, and worksite. The configuration should also minimize the effect of center of gravity shifts or have the ability to adjust for such shifts.

The primary concepts considered were (Figure 66):

- 16 thrusters in 4 identical clusters of 4
- 18 thrusters in 6 identical clusters of 3.

The four-thruster clusters suggests either of two arrangements on the MRWS cabin as shown in Figure 67. This concept resembles the Lunar Module (LM) thruster arrangement on the ascent stage that provided rotational and translational control during both descent and ascent. It should be pointed out that the system on LM was primarily used only for rotational control when the descent stage was attached with the associated major shift in the center of gravity. The configuration was optimized for combined rotational and translational control during ascent with the c.g. in the center of the thruster arrangement.

The four-thruster concept requires that the center of gravity of the MRWS assembly, including items being transported, be close to the center of the thruster plane. Displacement of the center of gravity from the optimum center location will

TABLE 27

ADDITIONAL EQUIPMENT REQUIRED FOR FREE FLYER MRWS

EQUIPMENT	LOCATION			WEIGHT (lb)
	CABIN	EXTERNAL	AFT BAY	
• RCS				(419)
- H_2 TANKS/REG/FILTER		X		12
- ISOLATION/FILL VALVE		X		3
- FUEL TANK/FILTER		X		337
- SHUTOFF VALVE		X		1
- THRUST NOZZLES (16)		X		30
- THRUST VALVES (16)		X		16
- PLUMBING		X		20
• GN&C				(172)
- IMU	X			42
- COMPUTER	X			30
- PULSE TORQUE ASSY	X			15
- POWER & SERVO ASSY	X			20
- ATT/TRANSL ASSY	X			30
- COUPLING DATA UNIT	X			35
• RADAR				(46)
- ANTENNA		X		30
- TRANSPONDER			X	16
• EPS				(880)
- BATTERIES & CONTROL		X		890
ADDITIONAL EQUIPMENT TOTAL				1517
CLOSED CABIN EQUIPMENT TOTAL		1709 lb		1709
FREE FLYER EQUIPMENT WEIGHT TOTAL				3226

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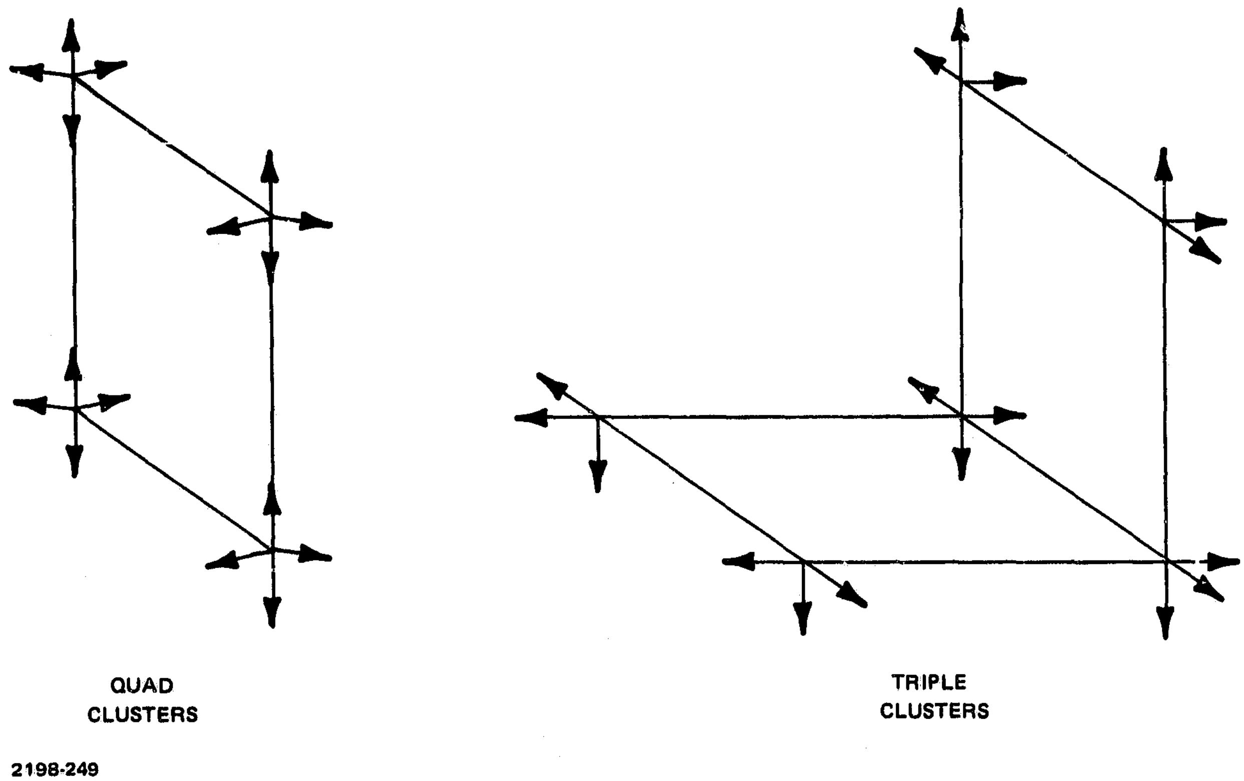

Figure 66. Candidate Thruster Arrangements

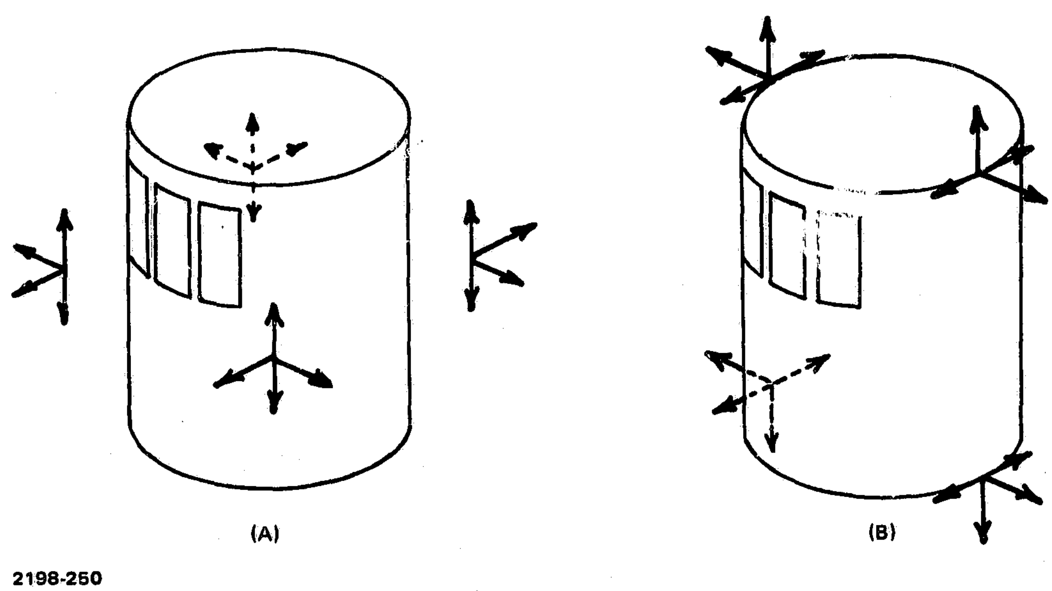

Figure 67. Four-Thruster Cluster Options

require duty cycling of thrusters to counteract unwanted rotational effects during translation. Option (a) appears attractive for center of gravity motions in the fore/aft direction but has the disadvantages of significant plume impingement on the manipulators and the primary work zone. Option (b) causes similar plume impingement of the work zone but not in the manipulator mount areas.

The three-thruster clusters concept for the MRWS is shown in Figure 68. The primary advantage of this concept is that no thrusters are firing in the forward, upper quadrant of the vehicle which is the primary zone where manipulator work is conducted. This concept requires a center of gravity location near the center of the rectangular parallelpiped formed by the clusters. This concept provides more flexibility in the evolutionary development of the MRWS concepts by being less sensitive to center of gravity location shifts. This concept lends itself equally well to mounting the jets on a cargo platform or on the cabin when there is no cargo platform with the desired change in moment arms. The four-thruster approach, on the other hand, would always require at least one pair of clusters to be mounted on the cabin. Consequently, the three-thruster approach was selected as the baseline for the MRWS. A summary comparison of the two basic approaches considered is shown in Table 28. An expanded development of the selected configuration is shown in Figure 69 including the firing logic for translation and rotation.

4.2 CONTROLS AND DISPLAYS

The controls and displays developed for the free flyer MRWS are based on the cherry picker configuration. Functions unique to the cherry picker were eliminated and the flight control/propulsion functions unique to the free flyer were incorporated in the panels at preferred locations. The selected controls and displays are listed in Table 29 with functions, dimensions, and power indicated. The average power consumption for various modes of operation are also shown including station-to-station translation, hovering free flight, stabilized operation at a worksite, with and without CCTV, and a powered-down, no activity condition.

4.3 ELECTRICAL POWER

Battery versus Fuel Cells

Stored energy systems are the only practical power source candidates for a non-fixed base MRWS. Interference and blockage eliminates solar panels and radioisotape dynamic power systems require excessive radiator area.

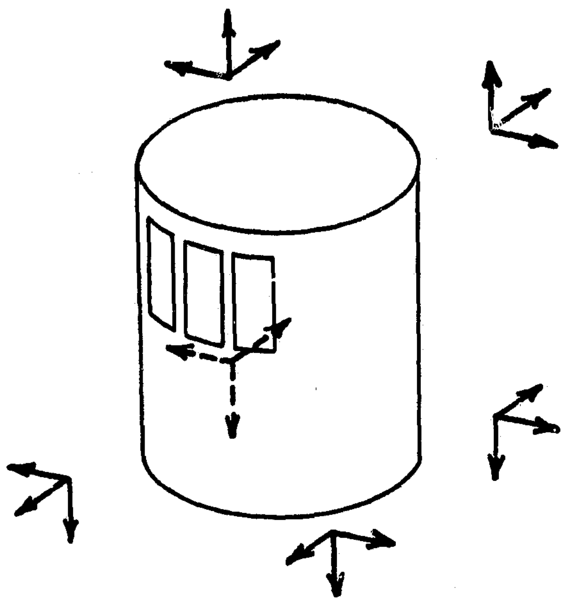

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Figure 68. Three-Thruster Cluster Configuration

TABLE 28

CANDIDATE THRUSTER CONCEPTS COMPARISON

CONCEPT	ADVANTAGES	DISADVANTAGES
QUAD CLUSTER	• MIN. NO. OF THRUSTERS (16) • SIMPLE FIRING LOGIC	• MAX. CABIN PLUME IMPINGEMENT • TRANSLATION PERFORMANCE SENSITIVE TO CG MOVEMENT OUT OF PLANE • CABIN MOUNT REQUIRED
TRIPLE CLUSTER	• MIN. PLUMES IN WORK VOLUME • MIN. MANIPULATOR IMPINGEMENT • ADAPTABLE TO CG LOCATION SHIFTS • CABIN MOUNT NOT REQUIRED	• MAX. NO. OF THRUSTERS (18) • COMPLEX SELECTION LOGIC

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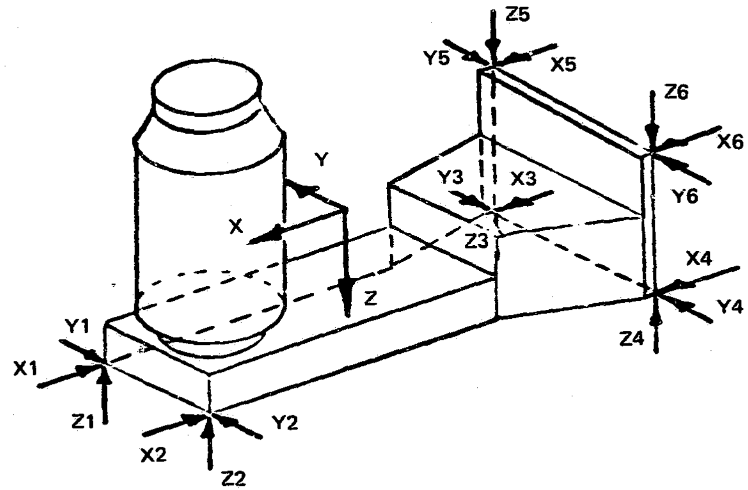
THRUSTER LOCATIONS &
ORIENTATIONS



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FIRING LOGIC

THRUSTER	TRANSLATION (ROTATION COMPENSATION)						ROTATION					
	X		Y		Z		X		Y		Z	
	+	–	+	–	+	–	+	–	+	–	+	–
X 1		●			(●)					●	●	
X 2		●			(●)					●		●
X 3	●											●
X 4	●										●	
X 5	●				(●)					●		
X 6	●				(●)					●		
Y 1				●								
Y 2			●									
Y 3				●								
Y 4			●									
Y 5												
Y 6												
Z 1		(●)				●			●			
Z 2		(●)				●			●			
Z 3				(●)		●		●				
Z 4			(●)			●	●					
Z 5		(●)	(●)		●		●		●			
Z 6		(●)		(●)	●			●	●			

Figure 69. Thruster Configuration

TABLE 29

FREE FLYER MRWS – CONTROLS AND DISPLAYS

FUNCTION	PANEL AREA ($in.^2$)	DIMENSIONS (in.) W	H	D	AVG POWER (W)
I FRONT PANEL	(317)				
• ALPHANUM./GRAPHIC	224	8	7	6	50
• KEYBOARD	36	6	6	6	5
• CAUTION & WARNING	10	2	2.5	2	–
• MASTER STOP	4	1	4	2	–
• CCTV CONTROL	8	4	2	2	–
* • ATT./ATT. RATE	16	4	4	4	5
* • RANGE/RANGE RATE	6	2	3	3	5
* • VELOCITY	9	3	3	3	5
* • POSITION COORDINATES	4	2	2	2	5
II L FRONT LEFT PANEL	(72)				
• TTCA	–	–	–	–	–
• AUDIO	28	7	4	3	–
• INTERIOR LIGHTS	16	4	4	3	40/20
* • RADAR CONTROL	28	7	4	3	5
II R FRONT RIGHT PANEL	(99)				
• ACA	–	–	–	–	–
• GRAPPLER CONTROL	15	5	3	3	–
• EXTERIOR LIGHTS	36	6	6	3	5
* • RCS SWITCHING	16	4	4	2	–
* • RCS STATUS	16	4	4	2	5
* • RCS SWITCHING	16	4	4	2	–
III LEFT PANEL	SAME AS CLOSED CHERRY PICKER				
IV RIGHT PANEL					
V RIGHT UPPER					
VI OVERHEAD PANEL					
* FREE FLYER UNIQUE				TOTALS	457 MAX SITE 352 MIN SITE 278 TRANSLA. 116 MIN

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Of the various battery options, nickel cadmium appears to be the best compromise from a performance/cost standpoint. Although promising lower weight and longer life, the metal-hydrogen batteries are not yet proven and impose a large volume penalty. The silver compound systems are lighter and smaller, but have limited cycle life and pose voltage regulation and recharge problems.

Existing and advanced Shuttle fuel cells were considered with cryogenic and gaseous reactant storage. Gaseous storage requires simpler installation and controls, but high storage pressures must be used to realize a significant volumetric advantage over batteries.

Figure 70 depicts the substantial weight and volume advantage afforded by fuel cells over NiCd batteries. For the same mass, fuel cells can operate about 20 times longer than batteries at a given load, and 8-10 times longer at equal volume. The values shown reflect advanced NiCd batteries, advanced Shuttle fuel cells with (1) existing Shuttle cryogenic tanks and (2) tailored 3300 psi composite tanks.

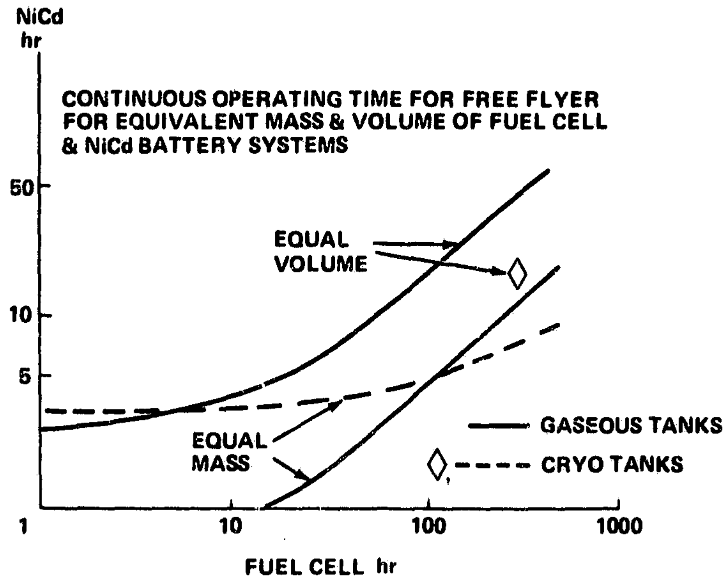
Based on specific mass/volume, batteries could only be considered for the short (9 hr) recharge cycle regime, whereas fuel cells are attractive for seven or more days of continuous operation.

The advanced Shuttle fuel cell provides about twice the life and operates at a higher temperature than the existing system. Radiator areas for the advanced fuel cell are comparable to those required for NiCd batteries.

Use of the Shuttle fuel cell can also accommodate MRWS power levels up to 7-12 kW, providing wide design/mission flexibility. Table 30 lists the additional electrical power that is required for the Free Flyer MRWS that must be added to the closed cabin power shown in Table 22.

Conclusions

Fixed-base MRWS versions can be powered directly via hardwire. For mobile versions of the MRWS, fuel cells provide the greatest flexibility and long continuous service. There is some question however, of the advisability of storing hydrogen at very high pressure. This could dictate use of the more complicated cryogenic reactant storage. Should installation/control of the cryogenic system prove undesireable, NiCd batteries could be a backup, but permit only short work intervals between recharge. All emergency requirements can be satisfied with a small NiCd battery.



- ENERGY SOURCES
  - √ – STORAGE
  - – SOLAR COLLECTOR
  - – RADIOISOTOPE DYNAMIC PWR SYS
  - – FACILITY PWR
- ENERGY STORAGE APPROACHES
  - – BATTERIES
    - √ o NiCD
    - o NiH_2
    - o AgH_2
    - o AgZu
    - o AgCd
  - – FUEL CELL
    - ○ SHUTTLE
    - ○ ADVANCED SHUTTLE

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Figure 70. Subsystem Options – Electrical Power

Consumable storage volumes one based on use of 3300 psi tanks similar to those used on the Shuttle. Additional volume could be saved if higher storage pressure was used. Composite 5000 psi tanks are being developed and might be considered for MRWS.

The issue of recharge time, maintenance difficulty/frequency, mission effectiveness and cost must be addressed through an optimization study before firm requirements one established for consumable/electrical energy storage. For example, the desirability of long, continuous operation with fuel cells must be compared to the use of simpler, longer life batteries and cost of replacement and recharge.

4.4 PROPULSION

4.4.1 Control Authority Requirements

Desirable levels of rotational control authority were investigated by reviewing Lunar Module flight experience and corresponding astronaut comments (Table 31). As a result, a goal of 10 deg/sec^2 rotational acceleration was established as a design goal. It is recognized that this goal is difficult to achieve with the limited moment arms available, the magnitude of the vehicle inertias, and the desire to use available thrusters.

4.4.2 Tank Sizing

Propellant tank sizing involves estimating the amount of propellant required for the following four areas of usage:

- Translation (including orbital effects) - involves linear motion in the vicinity of a large space structure
- Stationkeeping - involves maintaining a fixed relative position with respect to a large space structure
- Attitude Control - involves a desired angular orientation
- Rotation - involves changing from one angular orientation to another in a required time.

The first two uses are dominated by the orbital mechanics of a small body, the MRWS, moving with respect to a very large body, e.g., a space construction platform. The maximum magnitude of this effect occurs for motion along the local

TABLE 30

FREE FLYER ADDITIONAL ELECTRIC POWER

EQUIPMENT	AVERAGE POWER (W)	
EXTERNAL LOCATION		
• RCS		(60)
- ISOLATION VALVE H_2	10	
- SHUTOFF VALVE N_2H_2	10	
- THRUST NOZZLE VALVES (16)	40	
CABIN LOCATION		(462)
• GN&C		
- IMU	150	
- COMPUTER	80	
- COUPLING DATA UNIT	10	
- PULSE TORQUE ASSY	5	
- POWER/SERVO ASSY	60	
- ATT/TRANS CONT ASSY	15	
• CONTROLS AND DISPLAYS	142	
AFT BAY LOCATION		(95)
• RADAR		
- TRANSPONDER	95	
ADDITIONAL COMPONENTS TOTAL		617
CLOSED CABIN TOTAL		2796
TOTAL ELECTRICAL POWER FREE FLYER		3413

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TABLE 31

LUNAR MODULE CONTROL AUTHORITY

MISSION PHASE	ANGULAR ACCELERATION (deg/sec^2)			
	X	Y	Z	
INITIAL DESCENT	6.3	5.7	5.7	"SLUGGISH"
HOVER	10.5	10.5	9.0	"GOOD"
LANDING	12.6	11.5	9.7	"GOOD"
LIFTOFF	21.0	42.0	21.0	"HOT"
RENDEZVOUS & DOCK	42.0	42.0	63.0	"HOT"

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vertical direction. Figure 71 shows the propellant consumption as a function of trip time for 1 and 10 km excursions produced by impulsive burns at the beginning and end of the maneuver (orbital rate = 10^{-3} rps).

Propellant consumption rates required to maintain a fixed position relative to the center of gravity of the main body are presented in Figure 72 for a 3200 kg MRWS with approximately three times more required to stay above or below the center of gravity than to the sides (out of plane). No propellant is used to maintain position for or aft of the main body.

Attitude control propellant consumption during limit cycle control has been analyzed for a general MRWS configuration. Typical consumption rates have been computed for a specific free flyer MRWS configuration as shown in Figure 73.

Rotation propellant requirements for the above free flyer configuration have been developed using both GN_2 0.1 lbf thrusters and N_2H_4 5.0 lbf thrusters. The variation of slew time as a function of slew angle for 0.1 and 1.0 deg/sec slew rate in Figure 74a with propellant consumption versus slew rate in Figure 74b. One deg per sec has been selected as the slew rate resulting in relatively short slew times with acceptable levels of propellant consumption.

A monopropellant hydrazine (N_2H_4) system using 5 lbf thrusters has been selected for both the translation and rotation functions. Propellant consumption for translation using gaseous nitrogen was found to be prohibitive. Choosing the same N_2H_4 system for rotational control avoids using a completely separate system while offering reduced weight advantages.

The following reference mission guidelines were selected as the basis for propellant estimation:

- Operating period: 10 hr
- Translation delta V corresponding to two 10 km trips in optimum (half orbit) time equals 40 m/sec total
- Stationkeeping propellant corresponding to continuous 5 km out-of-plane operation for 10% of operating period or 1 hr
- Operating period divided into 25% free-flying and 75% grappled operation

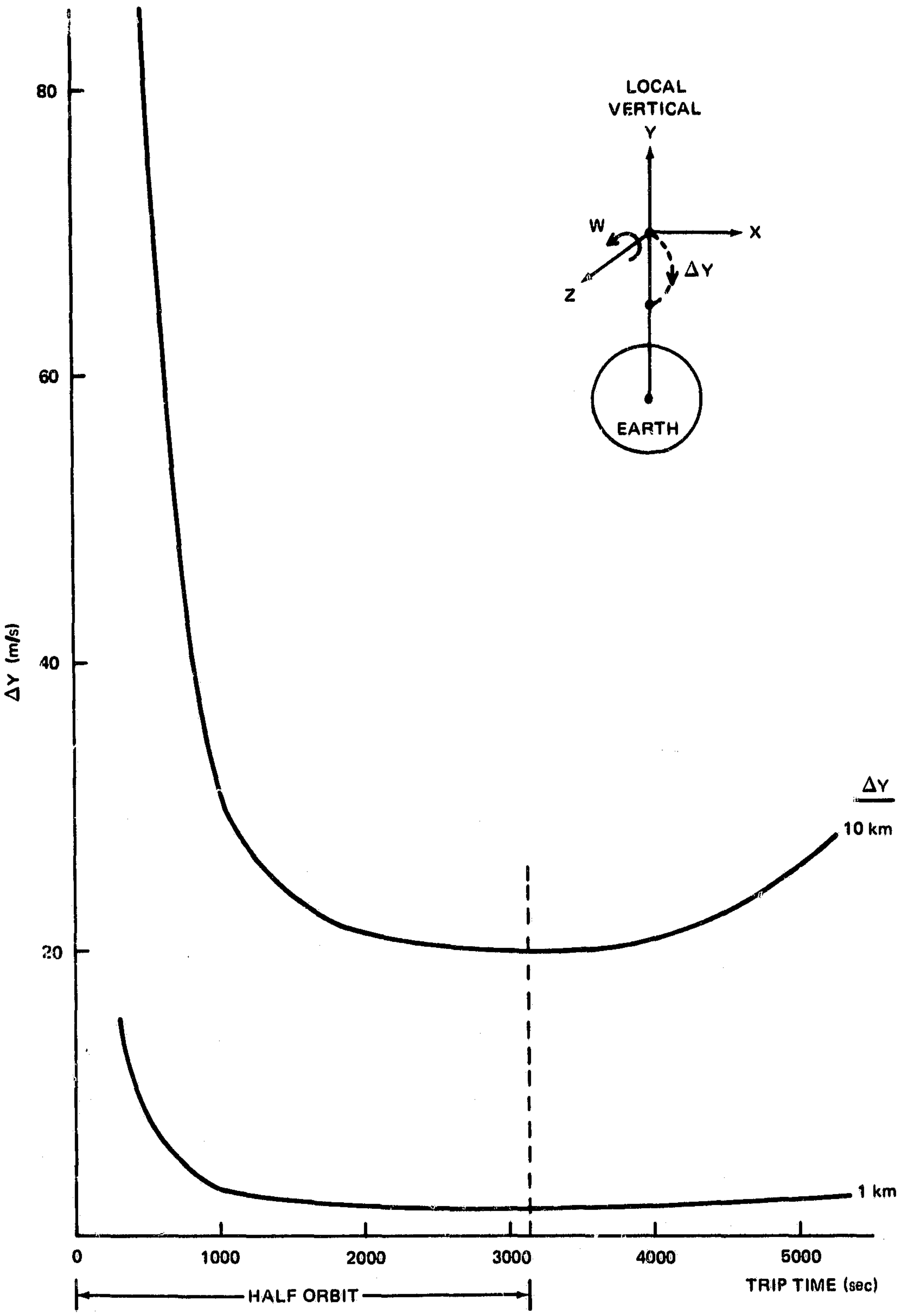

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Figure 71. Propellant Requirements for Vertical Transfer

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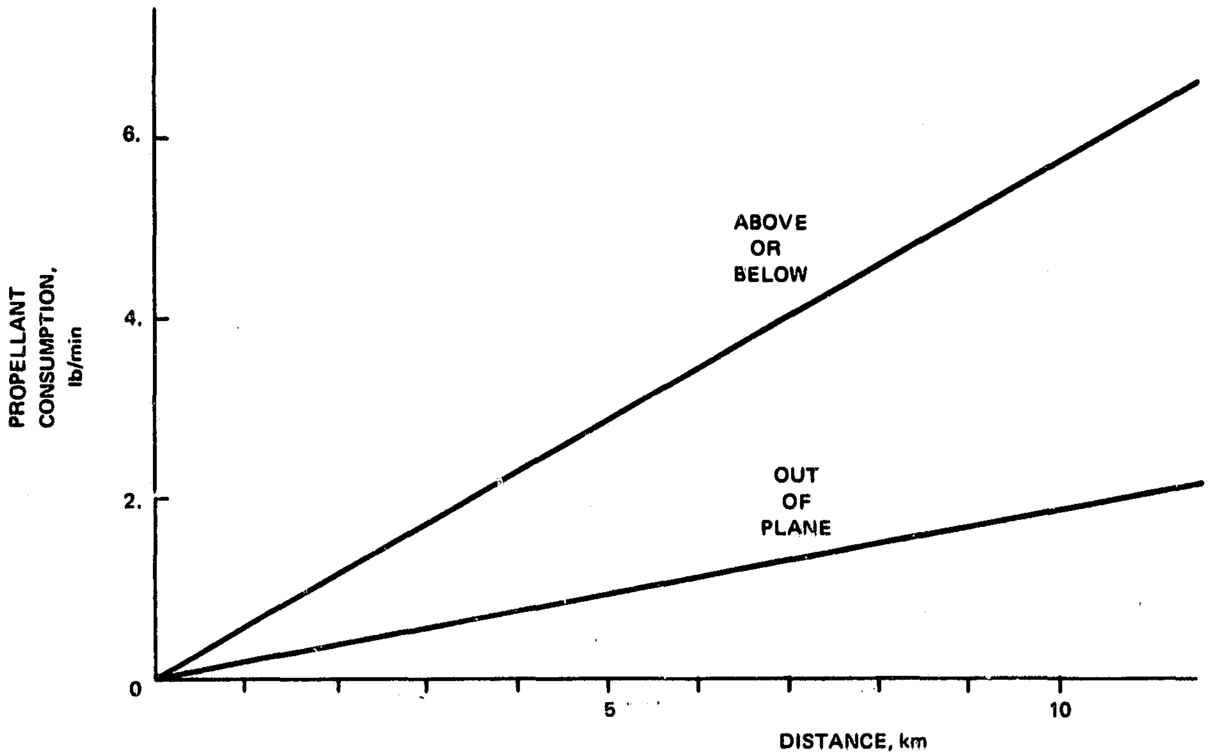

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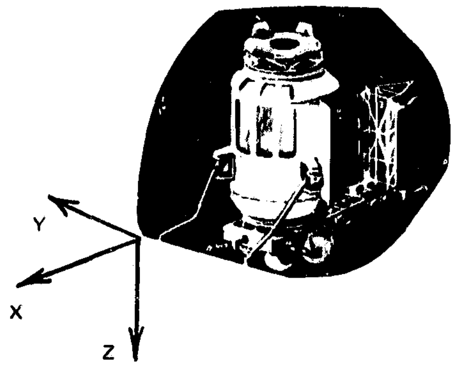
Figure 72. Stationkeeping Propellant

COORDINATES DEFINITION



INERTIAS

I_x = 3930 SLUG ft^2

I_y = 6650 SLUG ft^2

I_z = 5910 SLUG ft^2

CONTROL THRUST = 5 lbf

DEADBAND = 0.1 deg

MIN IMPULSE BIT = 40 m sec

GAS CONSUMPTION (lb/min):

AXIS	
X	0.00238
Y	0.00317
Z	0.00283

MOMENT ARMS

L_x = 11 ft

L_y = L_z = 14 ft

Isp = 225 sec (N_2H_4)

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Figure 73. Typical Consumption Rates for a Specific Free Flyer MRWS Configuration

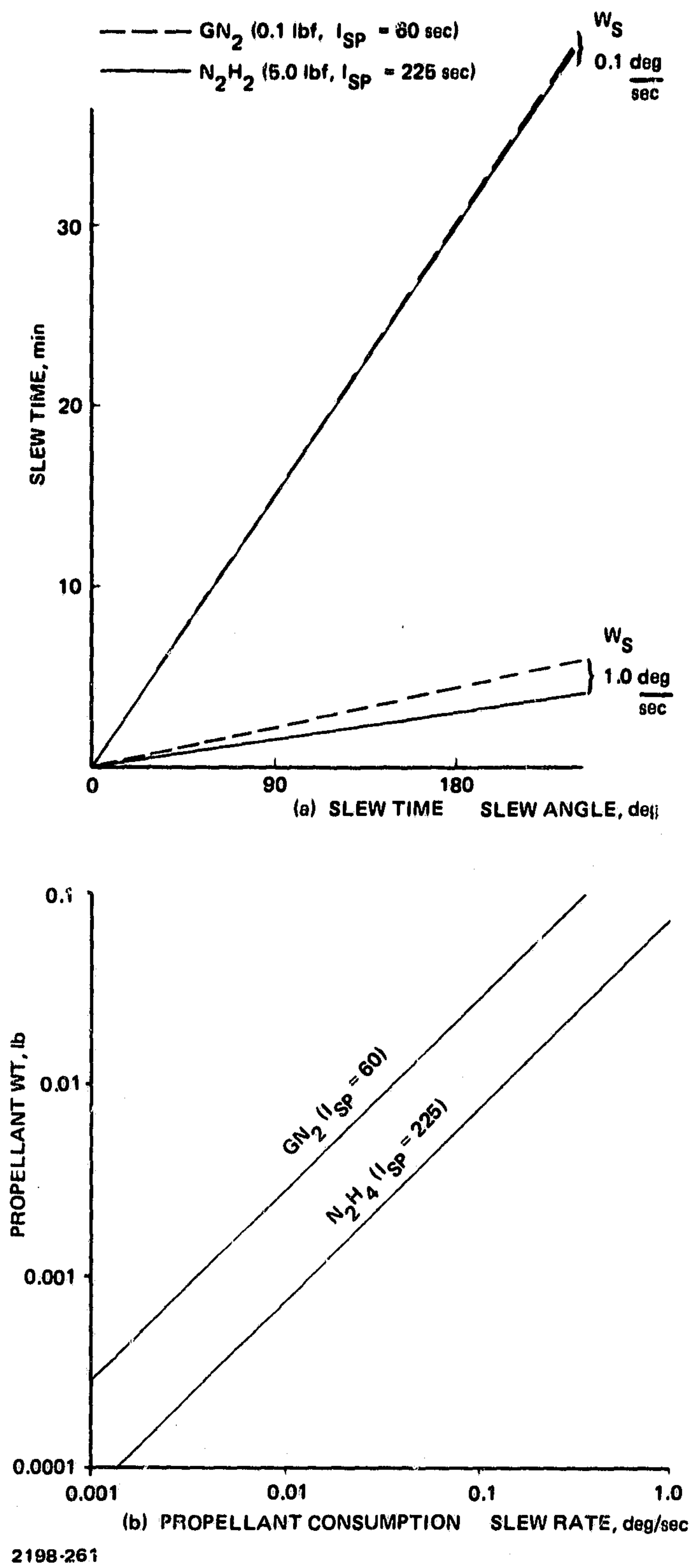

Figure 74. Slewing Requirements

- Slew rate = 1.0 deg/sec
- Two 5 lbf thrusters used for translation
- Twenty 180 deg slews per operating period.

The resulting N_2H_4 propellant estimates for the operating period are as follows:

• Translation:	160. lb
• Stationkeeping:	60. lb
• Attitude Control:	2. lb
• Slewing:	3. lb
TOTAL	225. lb

This quantity of propellant requires a bladdered 24-in. diameter spherical tank weighing 19.5 lb. Operating time can be significantly extended by using four 16.5 in. diameter Multimission Modular Spacecraft tanks instead each with a capacity of 70 lb of propellant.